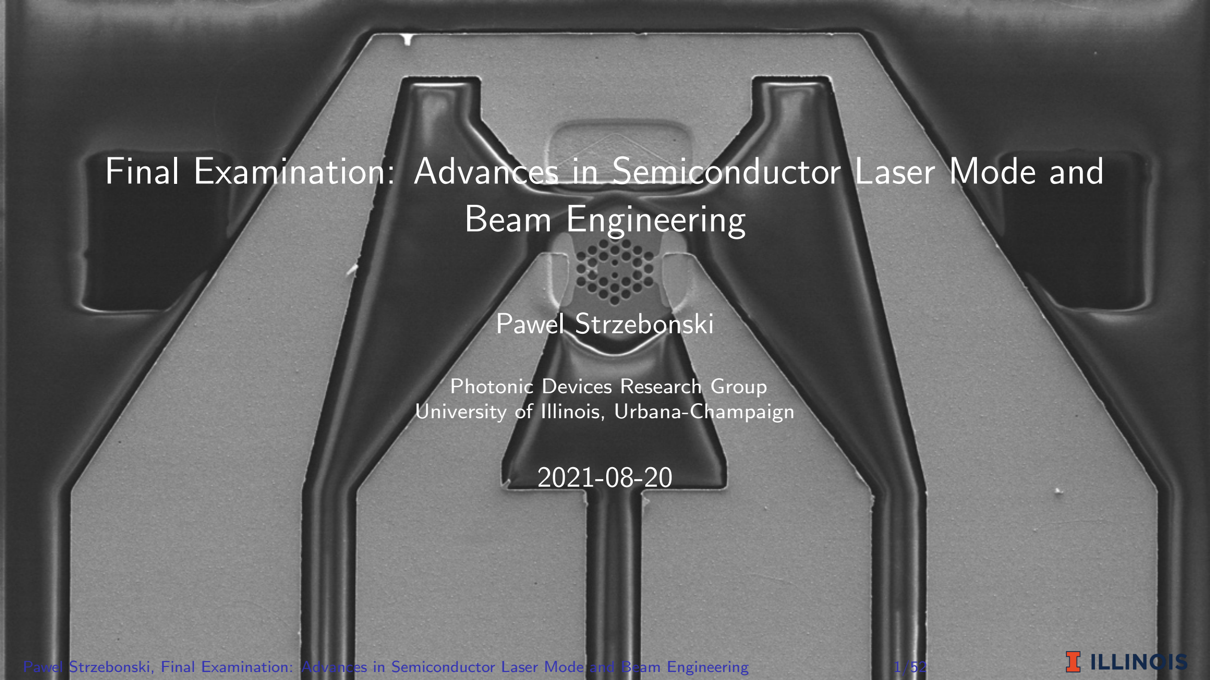

Final Examination: Advances in Semiconductor Laser Mode and Beam Engineering

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2021-08-20

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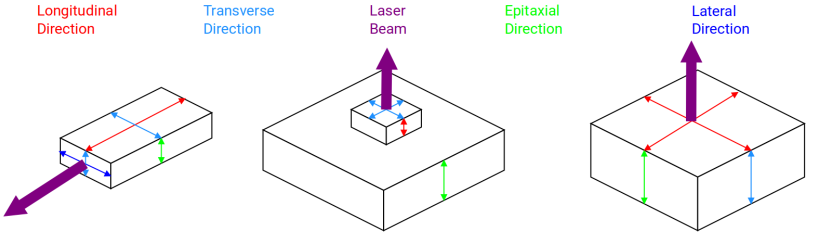
Laser Mode and Beam Engineering

- 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



Edge-Emitting Laser Vertical Cavity Surface Emitting Laser Photonic Crystal Surface Emitting Laser

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

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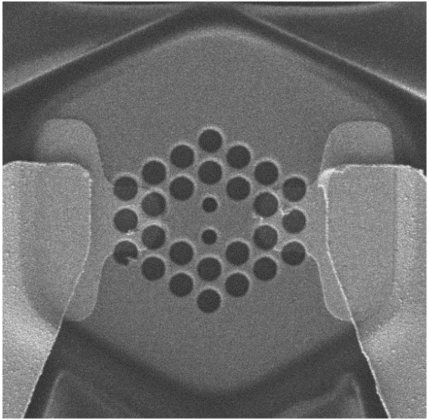
Photonic Crystal VCSEL Arrays

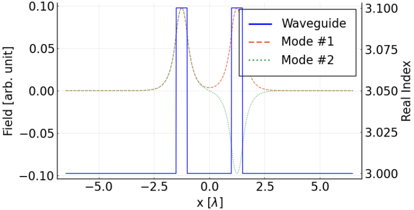
- Photonic crystal (PhC) is triangular lattice of circular etches
- PhC lattice period (Λ) of 4-5 μm
- PhC "Fill-factor" (FF), or diameter to period ratio of 0.6
- 2 VCSEL cavities defined by missing-hole defects in PhC
- Ion-implantation isolates cavities for individual control



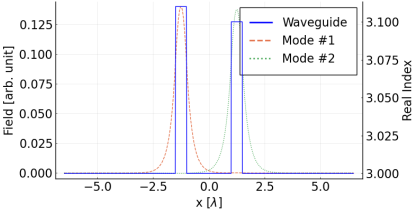
SEM image of a 2 × 1 PhC VCSEL array

Waveguide Array Coupling

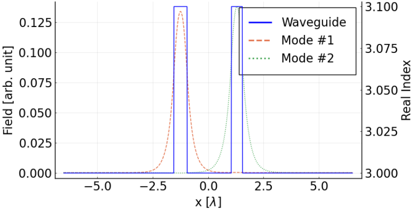
*Identical (coupled)**



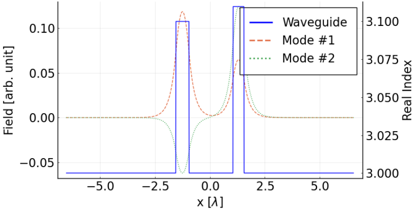
Different index (uncoupled)



Different size (uncoupled)



Different index/size (tuned to couple)



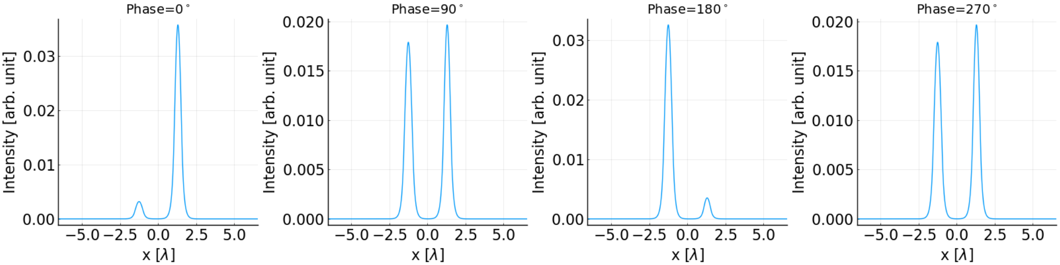
*Past coupled mode theory limited to symmetric arrays

Photon-Photon Resonance

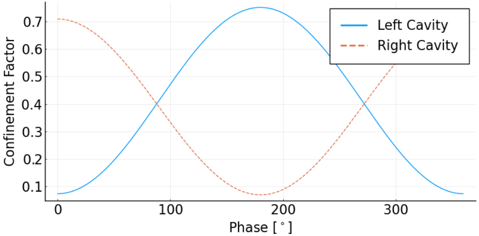
- Multi-mode effect, ≥ 2 modes interfere
- Interference shifts power between cavities
- Coupled mode theory:
  - Quantified as "coupling coefficient" (κ)
  - κ derived from modal effective index splitting
  - Limited to symmetric arrays
  - Previous method of choice
- Time-varying confinement factor (Γ) 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

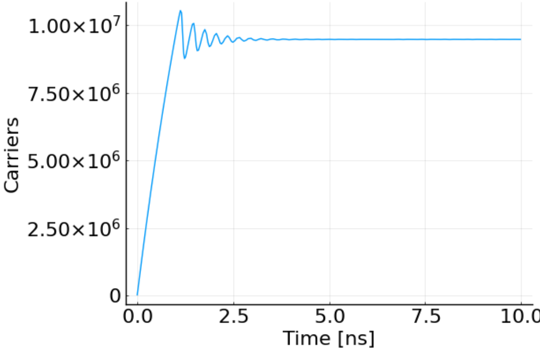


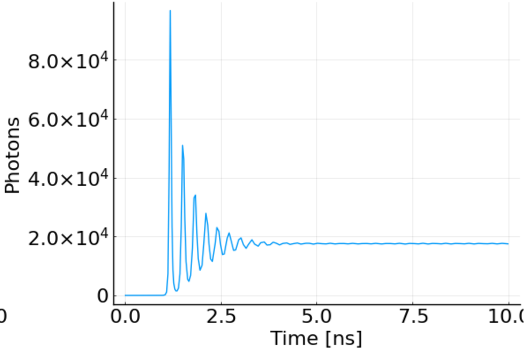
Confinement factors with left and right waveguides



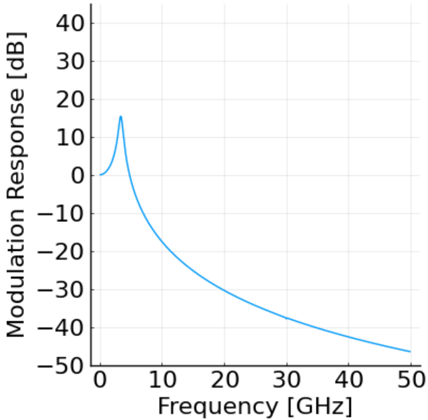
Time-Varying Confinement Factor: Rate Equations

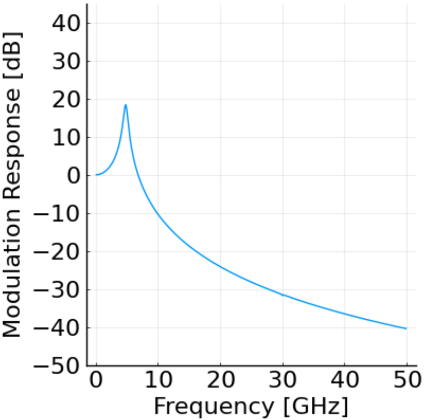
- Laser rate equations for change in photon and carrier populations
- Inspired by DFB work
- Translate analysis to multiple cavities and array supermodes
- Small-signal modulation response derived from rate equations
- Time-varying confinement factor is driving term, like current modulation





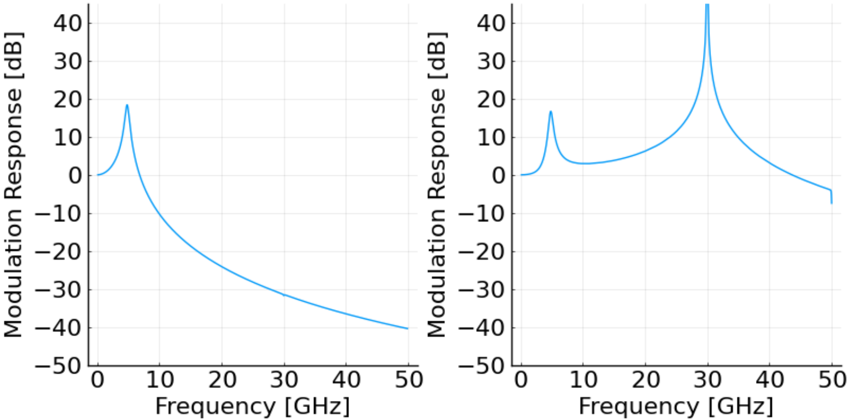
Single VCSEL vs Symmetric Dual-VCSEL Array





Some enhancement in array due to higher power, not PPR (prior coupled mode analysis agrees that no PPR enhancement in symmetric arrays)

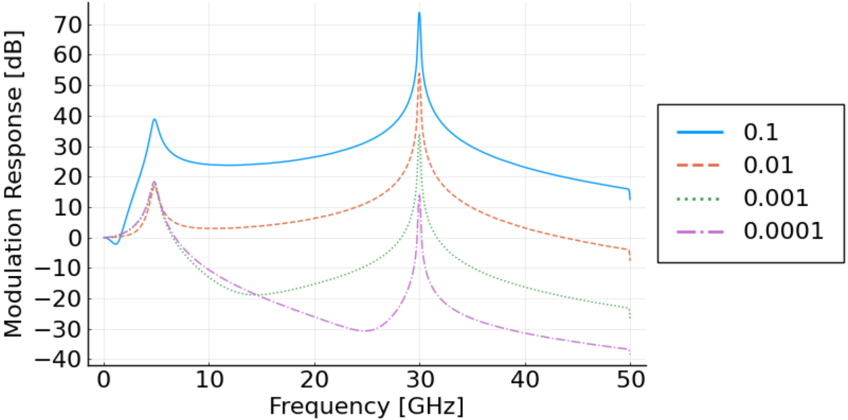
Symmetric vs Asymmetric Dual-VCSEL Array



Asymmetry enables photon-photon resonance at 30 GHz (now total array Γ varies, not just single cavity Γ)

Varying Asymmetric in Dual-VCSEL Array

Varying cavity Γ *by factor of* $1 \pm \gamma$ *(*γ *is asymmetry factor)*

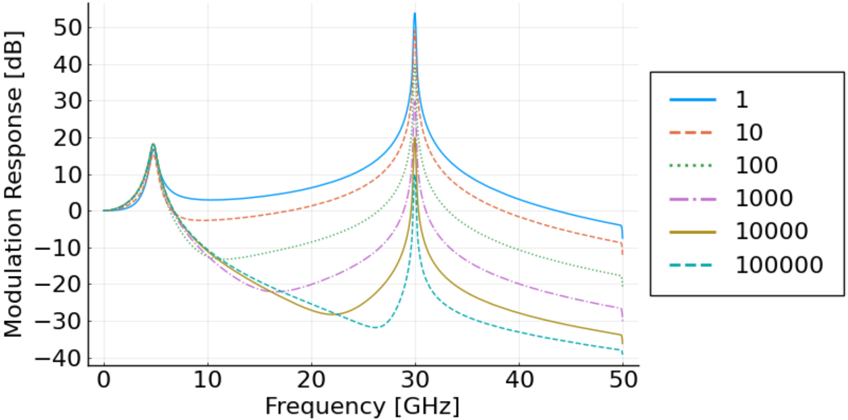


Greater asymmetry, stronger PPR

Even minimal asymmetry (e.g. fabrication tolerances) gives PPR effect

Varying Mode Suppression in Dual-VCSEL Array

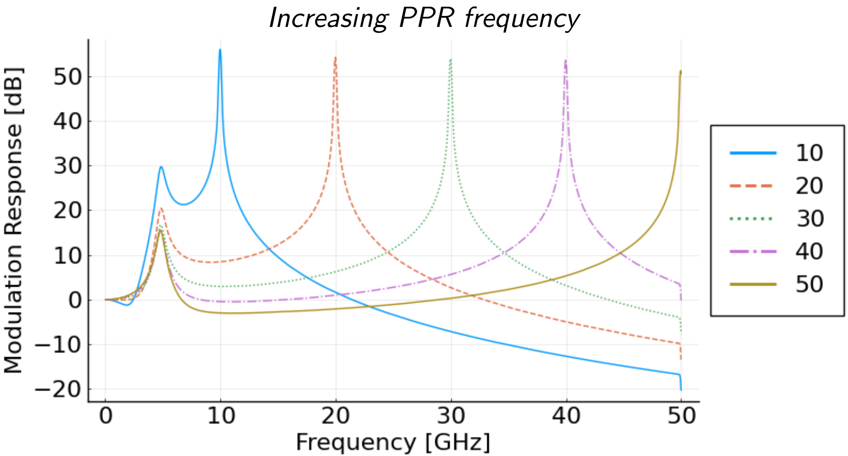
Varying mode suppression ratio $\left(MSR = \frac{P_{PrimaryMode}}{P_{SecondaryMode}}\right)$



Dual mode lasing gives stronger PPR

Even "single-mode" lasing ($10^3 = 30$ dB MSR) shows PPR effect

Varying PPR Frequency in Dual-VCSEL Array



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

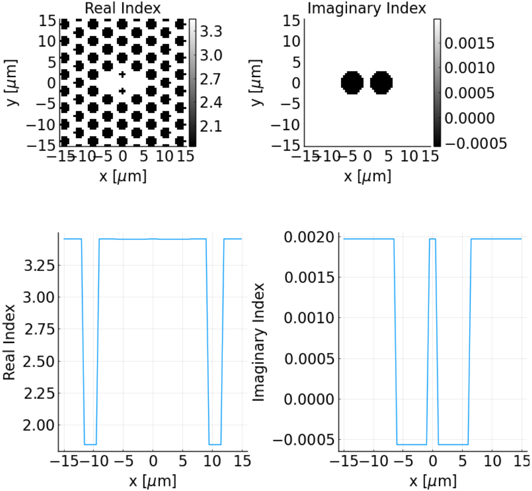
Reconciling PPR Analyses

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

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

Waveguide Modeling

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

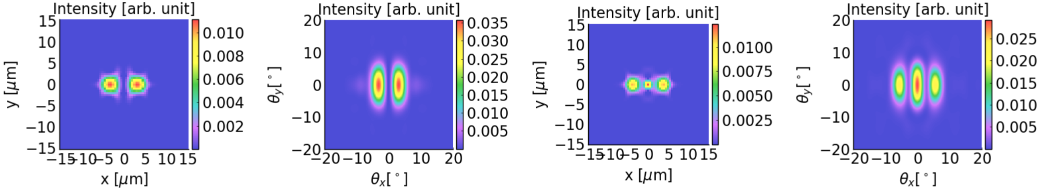


Index profile across array

VCSEL Array Supermodes

Out-of-phase mode

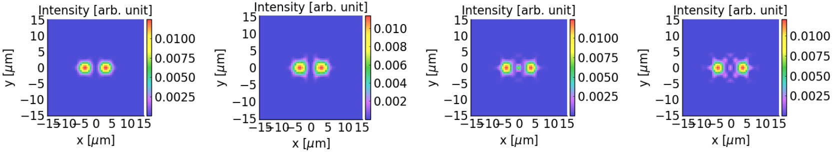
In-phase mode



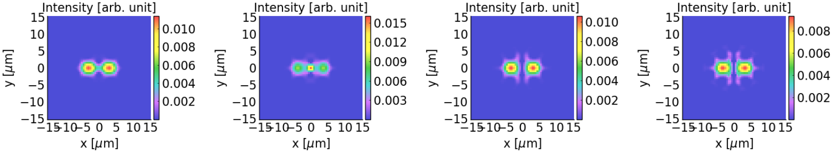
Mode and beam intensity profiles

VCSEL Array Supermodes with Increased Index Suppression (Carrier Injection)

Highest Γ mode:

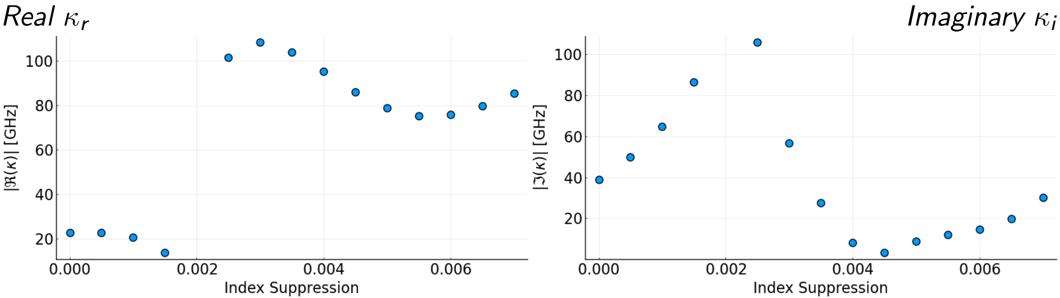


2nd highest Γ mode:



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

VCSEL Array Coupling with Index Suppression (Carrier Injection)



Real κ_r

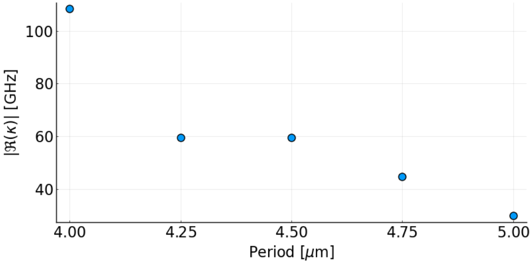
Imaginary κ_i

In-phase and out-of-phase modes switch at the dip in κ_i

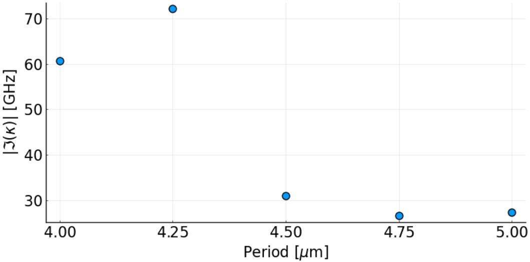
Increase in κ_r when third central lobe appears

VCSEL Array Coupling with PhC Period

Real κ_r



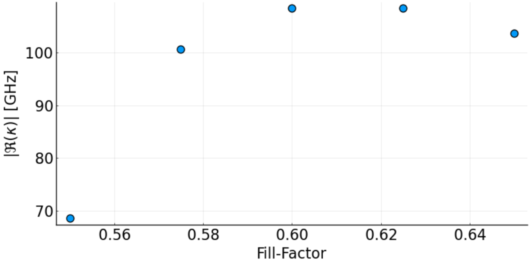
Imaginary κ_i



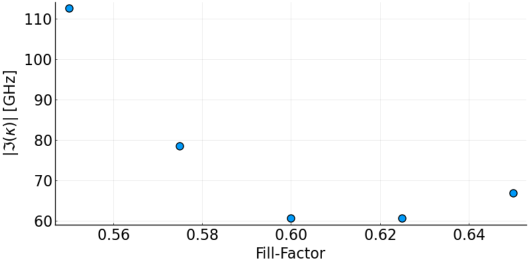
Both components of κ tend to decrease with Λ (weaker coupling with larger separation)

VCSEL Array Coupling with PhC Fill-Factor

Real κ_r



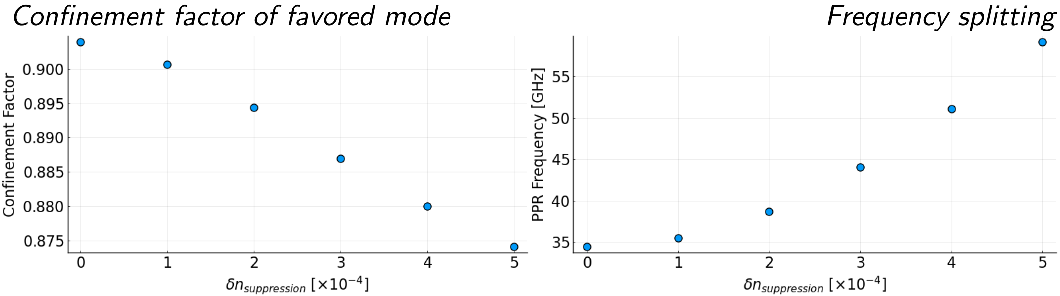
Imaginary κ_i



κ_r and κ_i counter-vary with fill-factor

Total κ magnitude varies much less than κ_r and κ_i individually

VCSEL Array Coupling with Suppression (Injection) Asymmetry



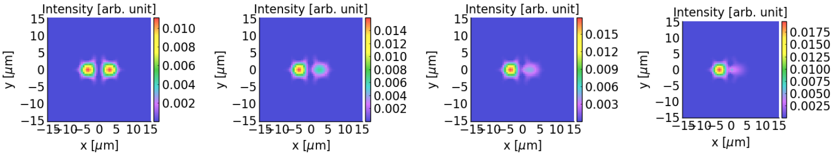
Confinement factor of favored mode

Frequency splitting

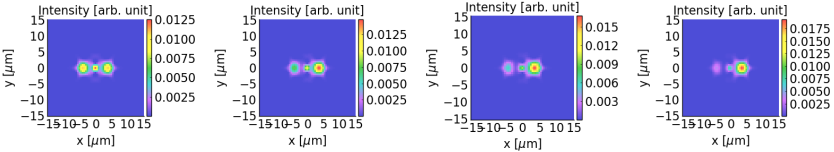
Increasing index suppression in one cavity by $\delta n_{\text{suppression}}$ lowers Γ, increases frequency splitting

VCSEL Array Modes with Increased Suppression (Injection) Asymmetry

Highest Γ mode



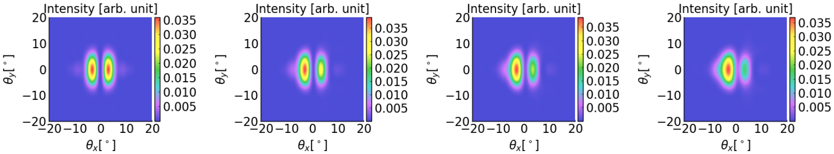
2nd highest Γ mode



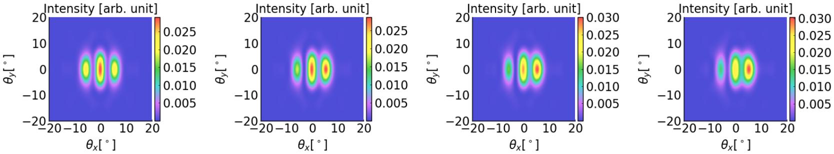
Asymmetric injection breaks down coupling, transitions from array supermodes to individual cavity modes

VCSEL Array Modes with Increased Suppression (Injection) Asymmetry

Highest Γ mode beam



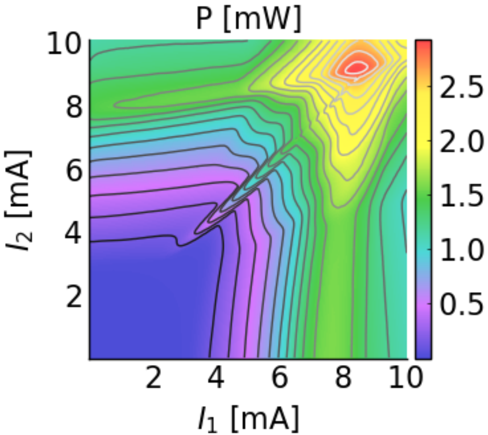
2nd highest Γ mode beam



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

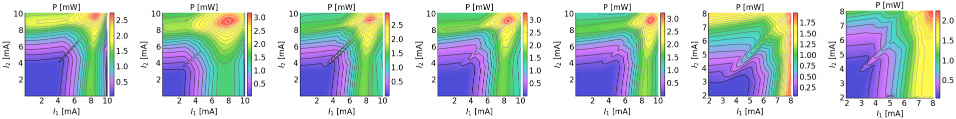
Experimental Analysis: Optical Power

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

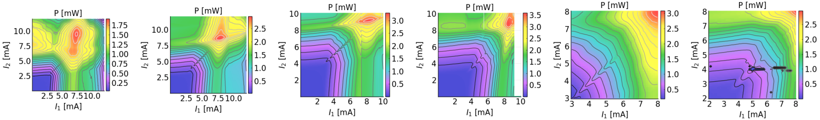


VCSEL Array Power Measurements

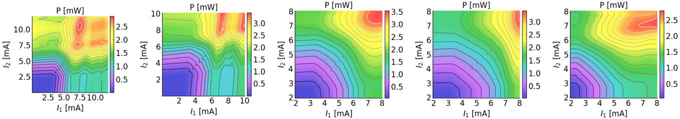
Design 1 (4 μm period):



Design 2 (4.5 μm period):

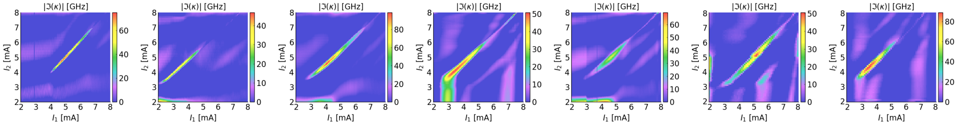


Design 3 (5 μm period):

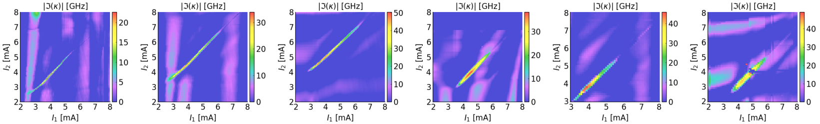


VCSEL Array Power Enhancement Estimates

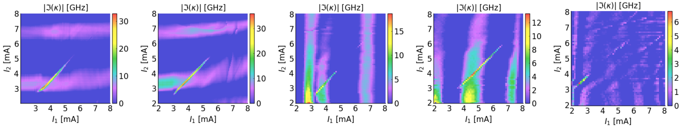
Design 1 (4 μm period):



Design 2 (4.5 μm period):

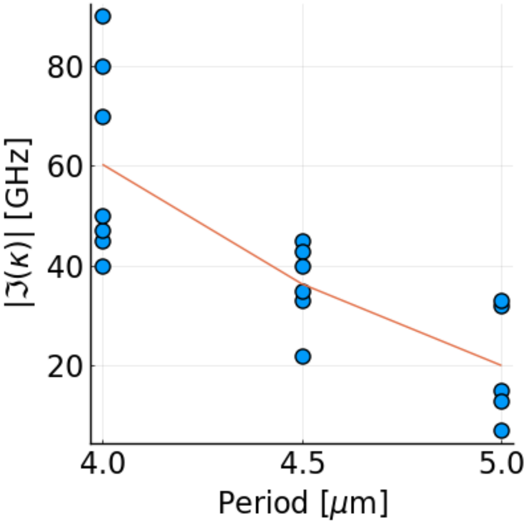


Design 3 (5 μm period):



Experimental Analysis: Optical Power Results

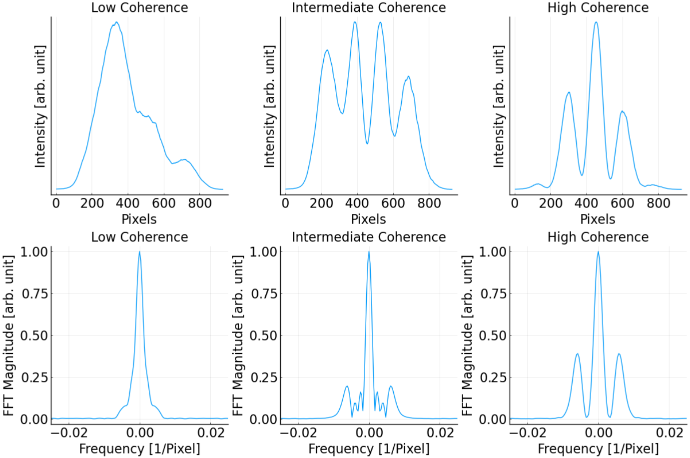
- Find max $|\kappa_i|$ for each array
- Plot individual and average imaginary coupling coefficients
- Larger PhC periods give smaller imaginary coupling coefficient (consistent with model)
- Some arrays show dip in $|\kappa_i|$ with increased current (consistent with model)



Experimental Analysis: Beam Profiles

- Coupling causes interference fringes in beam
- Past work has used “visibility” parameter to analyze beam profiles:
  - $V = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$
  - 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



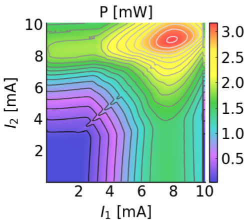
Higher coherence shows as stronger side-peak in Fourier transform of beam

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

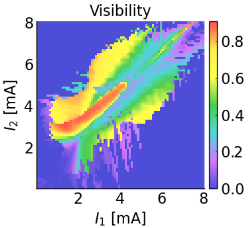
Phase of side-peak related to beam-steering

Experimental Analysis: Beam Analysis Compared

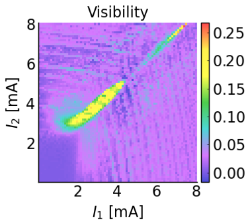
Array power



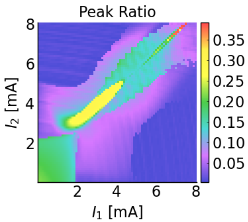
Simple estimate



"Tuned" estimate



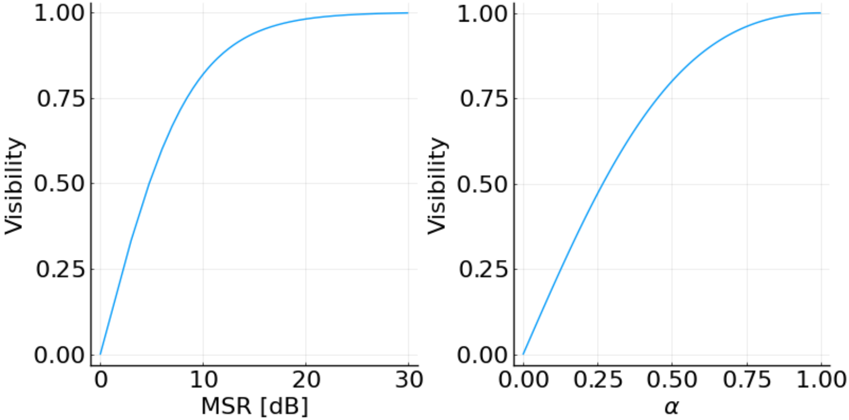
Fourier method



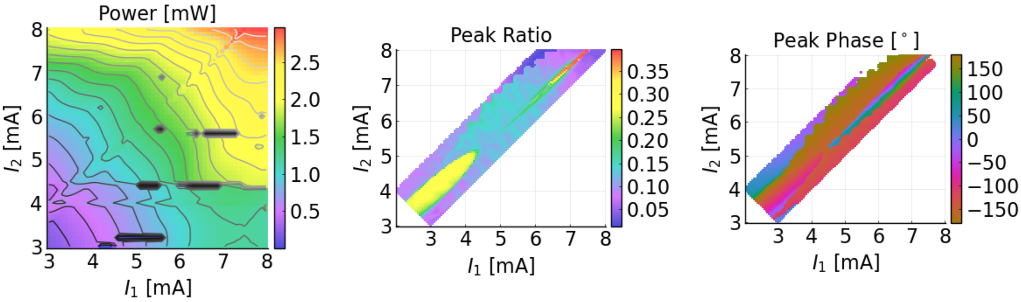
Visibility estimates are finicky, noisy (tuning involved)
Peak ratio needs no tuning, shows less noise

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



VCSEL Array Design 1 Beam Analysis

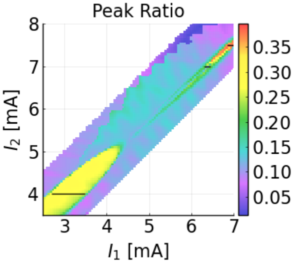


Two coherent ridges visible in peak ratio

Phase varies smoothly across coherent ridge (beam-steering)

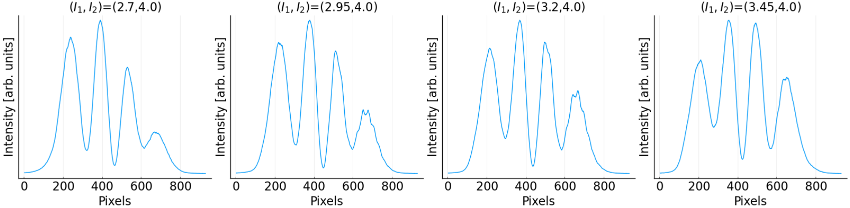
Large phase transition between the two (switch between in-phase-like and out-of-phase-like modes)

VCSEL Array Design 1 Beam Analysis

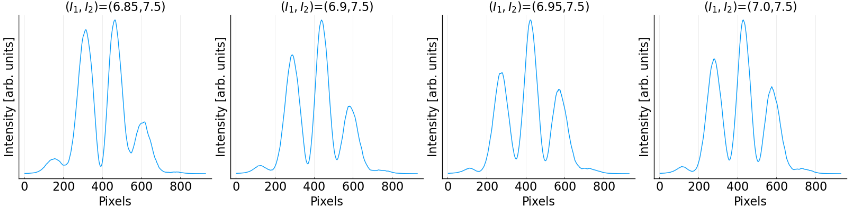


Locations of beam profiles marked

Low power coherent ridge:

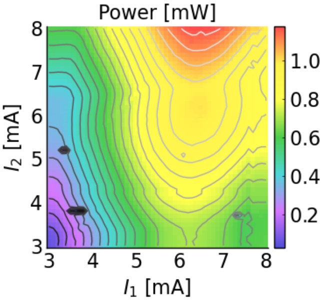


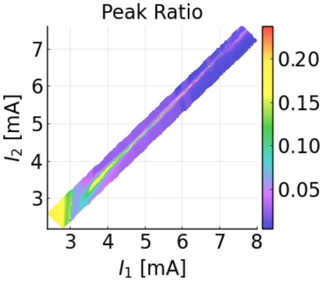
High power coherent ridge:

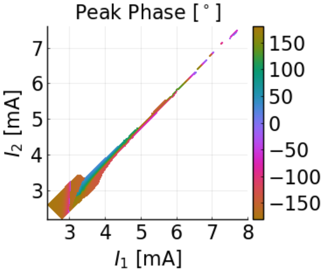


The two ridges show beam-steering and different beam profiles from the different supermodes

VCSEL Array Design 2 Beam Analysis



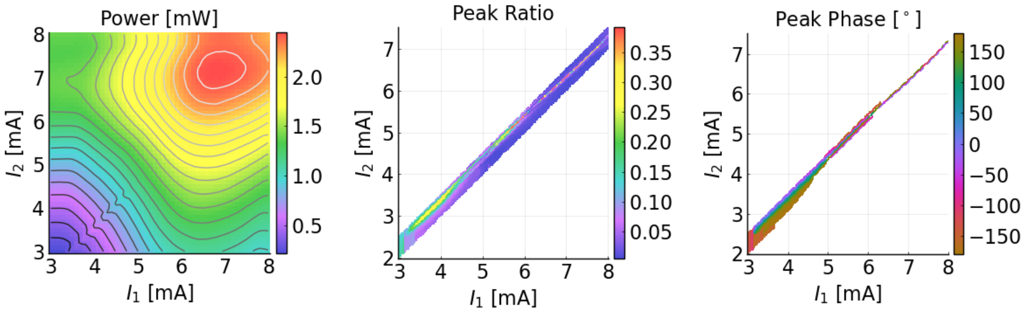




Much narrower coherent ridge visible in peak ratio

Phase varies smoothly across coherent ridge (beam-steering)

VCSEL Array Design 3 Beam Analysis

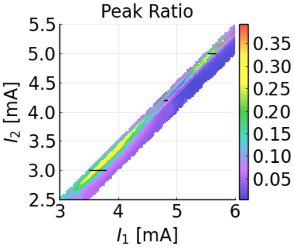


Narrower coherent ridge visible in peak ratio

Phase varies smoothly across coherent ridge (beam-steering)

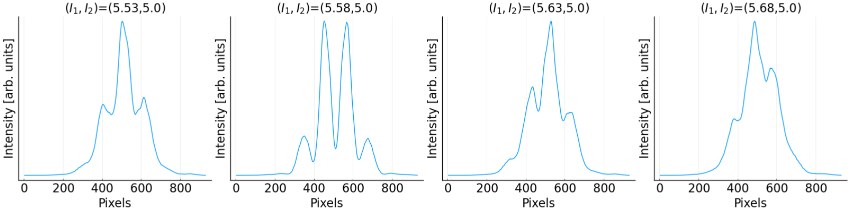
Ridge shows unusual low visibility features at center at some power levels

VCSEL Array Design 3 Beam Analysis

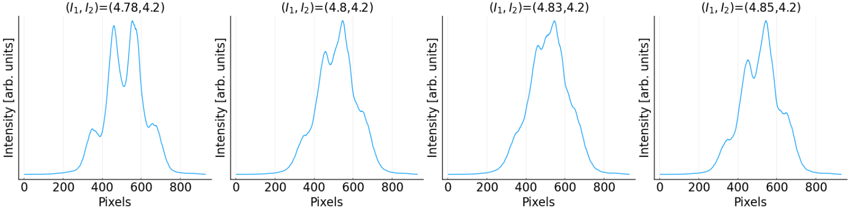


Locations of beam profiles marked

Rapid profile variation due to mode transitions:

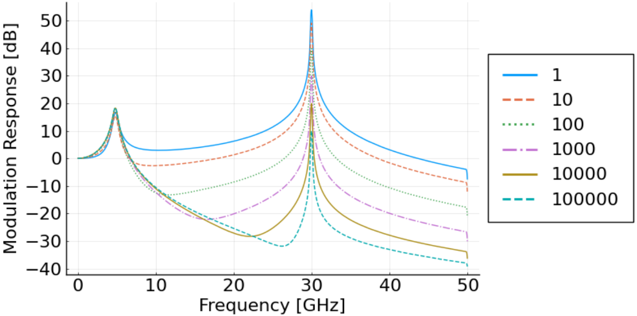


Dip in visibility at center of a ridge (lowered mode suppression ratio):



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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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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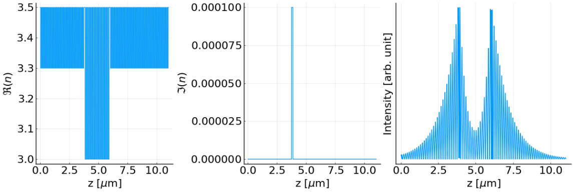
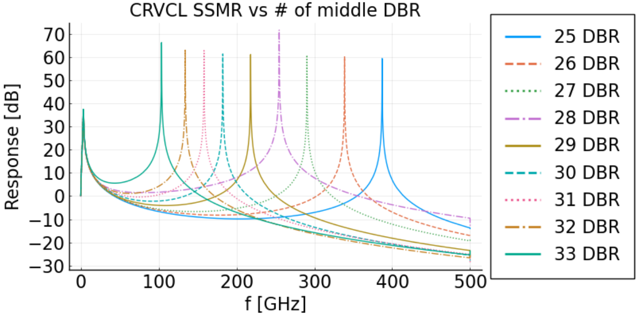
Experimental Validation

- 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

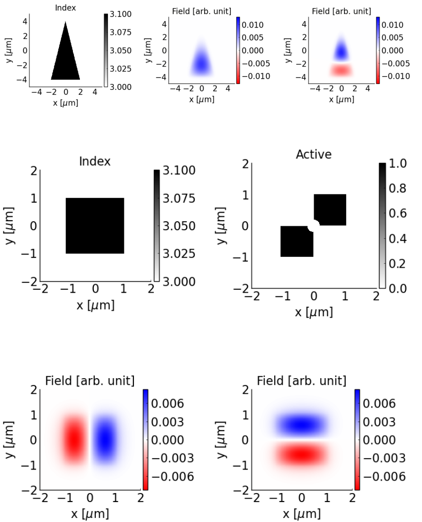
- Composite resonator vertical cavity lasers (CRVCLs) or dual-wavelength VCSELs
- Two epitaxialy defined cavities separated by a middle DBR section
- PPR effect from the beating of two longitudinal modes
- More complicated epitaxy but may be simpler to tune/operate (needs only a single active cavity)





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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Published Publications I

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

- Pawel Strzebonski and Kent Choquette. Complex waveguide supermode analysis of coherently coupled microcavity laser arrays. IEEE Journal of Selected Topics in Quantum Electronics, 28(1):1–6, January 2022.
- Raman Kumar, Pawel Strzebonski, Katherine Lakomy, and Kent D. Choquette. Orbital angular momentum modes from VCSELs using grayscale photolithography. IEEE Photonics Technology Letters, 33(16):824–827, August 2021a.
- Pawel Strzebonski and Kent D. Choquette. Guided mode expansion analysis of photonic crystal surface emitting lasers. In 2021 Annual Directed Energy Science and Technology Symposium. DEPS, 2021.
- Pawel Strzebonski, Harshil Dave, Katherine Lakomy, Nusrat Jahan, William North, and Kent Choquette. Computational methods for VCSEL array characterization and control. In Kent D. Choquette and Chun Lei, editors, Vertical-Cavity Surface-Emitting Lasers XXV. SPIE, March 2021a.

Published Publications II

- Raman Kumar, Pawel Strzebonski, Katherine Lakomy, and Kent D. Choquette. Orbital angular momentum modes from VCSELs using grayscale photolithography. IEEE Photonics Technology Letters, pages 1–1, 2021b.
- Pawel Strzebonski, William North, Nusrat Jahan, and Kent D. Choquette. Machine learning analysis of 2x1 VCSEL array coherence and imaginary coupling coefficient. In 2021 Conference on Lasers and Electro-Optics. IEEE, 2021b.
- Nusrat Jahan, William North, Pawel Strzebonski, Katherine Lakomy, and Kent D. Choquette. Extraction of coupling coefficient for coherent 2x1 VCSEL array. In 2021 Conference on Lasers and Electro-Optics. IEEE, 2021.
- William North, Nusrat Jahan, Pawel Strzebonski, and Kent D. Choquette. Spectral mode analysis of non-Hermitian phased microcavity laser array. In 2021 Conference on Lasers and Electro-Optics. IEEE, 2021.

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- Raman Kumar, Katherine Lakomy, William North, Pawel Strzebonski, and Kent D. Choquette. Integrated dielectric micro-optical elements on VCSELs using grayscale photolithography. In 2021 Conference on Lasers and Electro-Optics. IEEE, 2021c.
- Pawel Strzebonski, Katherine Lakomy, and Kent Choquette. Surface-etched laterally structured semiconductor laser diodes for mode engineering. In 2020 IEEE Photonics Conference (IPC). IEEE, September 2020a.
- Pawel Strzebonski and Kent Choquette. Machine learning for modal analysis. In 2020 IEEE Photonics Conference (IPC). IEEE, September 2020.
- Pawel Strzebonski, Raman Kumar, and Kent Choquette. Beam-steering in 2D via non-linear mapping of 1D beam-steering. In 2020 IEEE Photonics Conference (IPC). IEEE, September 2020b.

Published Publications IV

- Raman Kumar, Pawel Strzebonski, and Kent D. Choquette. Orbital angular momentum modes from coherently coupled VCSEL arrays. In 2020 IEEE Photonics Conference (IPC). IEEE, September 2020.
- Pawel Strzebonski and Kent Choquette. Direct semiconductor diode laser mode engineering and waveguide design. In 2019 IEEE Photonics Conference (IPC). IEEE, September 2019.
- Pawel Strzebonski. Semiconductor laser mode engineering via waveguide index structuring. Master's thesis, University of Illinois at Urbana-Champaign, 12 2018.
- Pawel Strzebonski, Bradley Thompson, Katherine Lakomy, Paul Leisher, and Kent D. Choquette. Mode engineering via waveguide structuring. In 2018 IEEE International Semiconductor Laser Conference (ISLC). IEEE, sep 2018.

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 2×1 VCSEL arrays
- Waveguide model and experimental validation of supermodes and coupling in 2×1 VCSEL arrays
- Guided mode expansion analysis of photonic crystal surface emitting lasers (journal version)