Machine Learning Analysis of 2 × 1 VCSEL Array Coherence and Imaginary Coupling Coefficient

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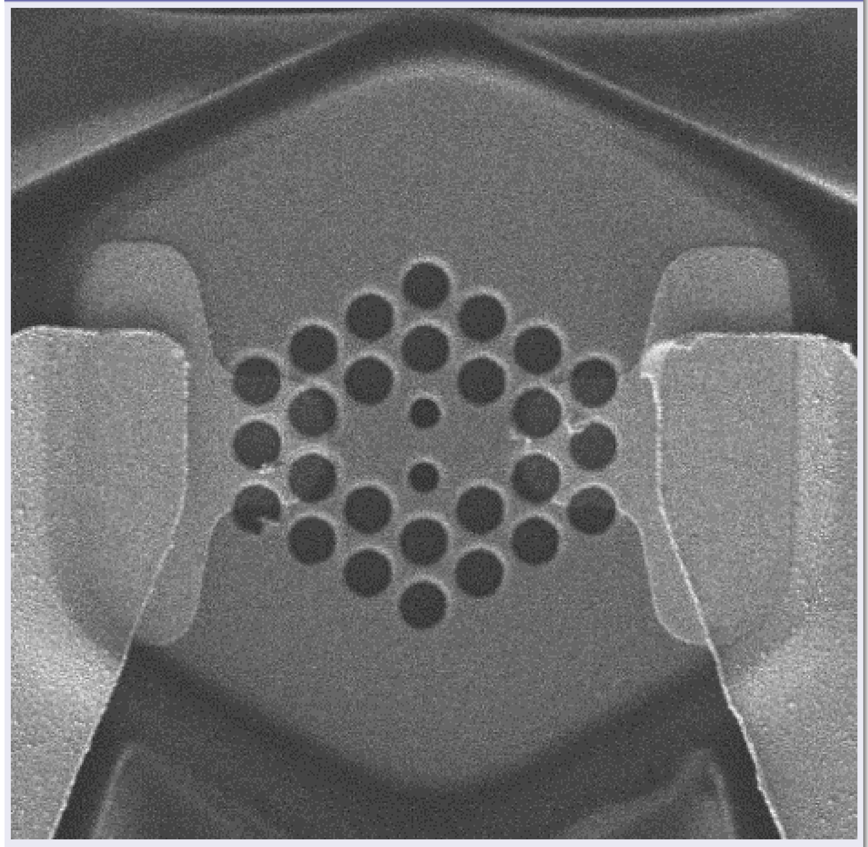
Introduction

- 2×1 arrays of optically coupled photonic crystal VCSELs
- When arrays are tuned to optical coherence:
  - Higher optical power [1]
  - Electrically-controlled beam-steering [1]
  - Lower intensity noise [1]
  - Higher modulation bandwidth [2]
- We explore machine learning for the analysis of optical coupling and coherence in VCSEL arrays

Challenges

- Coherently-coupled operation (and reaping benefits thereof) require tuning of driving currents
- Array design requires ability to characterize coherence and coupling behavior
- Many possible methods of analyzing coherence [3]
- Need to develop automated measurement and analysis methods for array

SEM Image



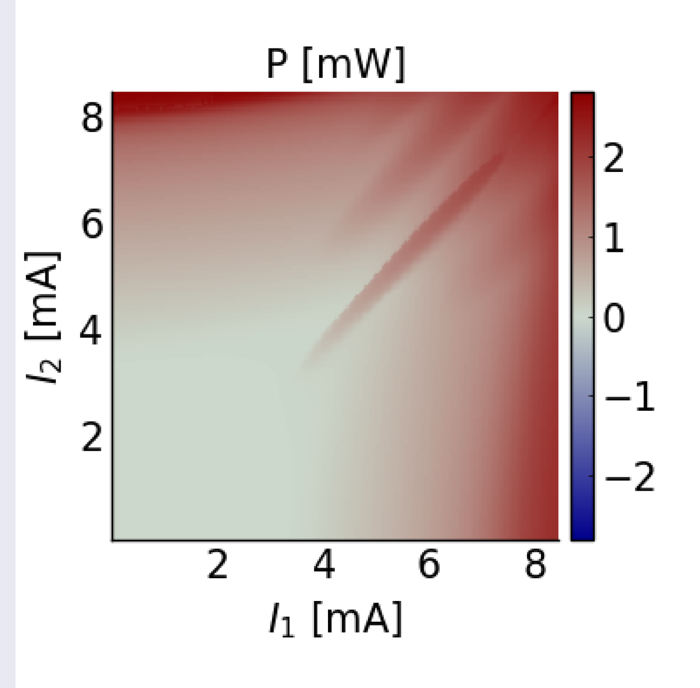
2×1 photonic crystal VCSEL array

Goals

- Optical power measurements can help characterize and tune to coherence
- Want to develop methods of analyzing large driving current–optical power datasets to derive coherence and coupling coefficient

Optical Power and Coupling Coefficient

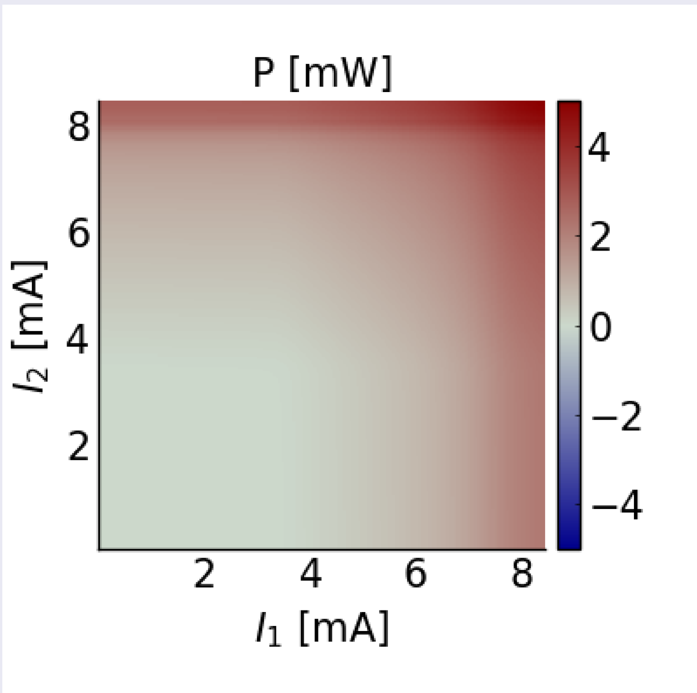
- Coherent coupling leads to array optical supermodes
- Optical supermodes can better extract gain from the array, leading to enhanced optical power
- The degree of power enhancement, ΔP_{total}, is related to the imaginary coupling coefficient κ_i:
  $|\kappa_i| \propto \frac{\Delta P_{\text{total}}}{a + \Delta P_{\text{total}}}$
  for some constant a [4]



"Coherent ridge" along the diagonal indicates coherently coupled operation

Naive Approach

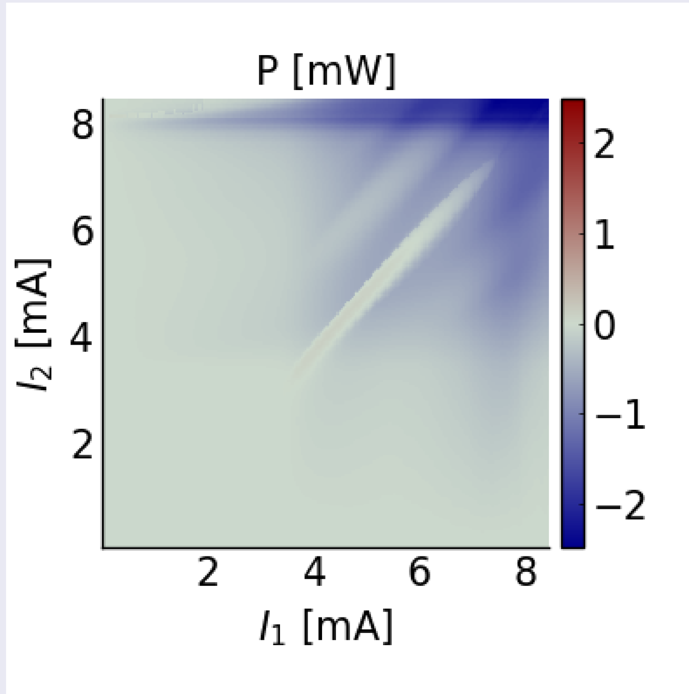
- Want to calculate coherent optical power enhancement
- Need to know what the uncoupled array power would be
- "Naive" approach is to estimate this as sum of individual element powers:
  $P_{\text{total,uncoupled}}(I_1, I_2) \approx P_1(I_1) + P_2(I_2)$
  For driving currents $I_{1,2}$ and element optical powers $P_{1,2}$



Naive estimate of uncoupled array power

Issues

- We calculate coherent power enhancement using naive estimate of uncoupled power
- Results show no enhancement nearly everywhere (even on the coherent ridge)
- Naive approach does not incorporate for thermal cross-talk affecting element power even in uncoupled regime [5]

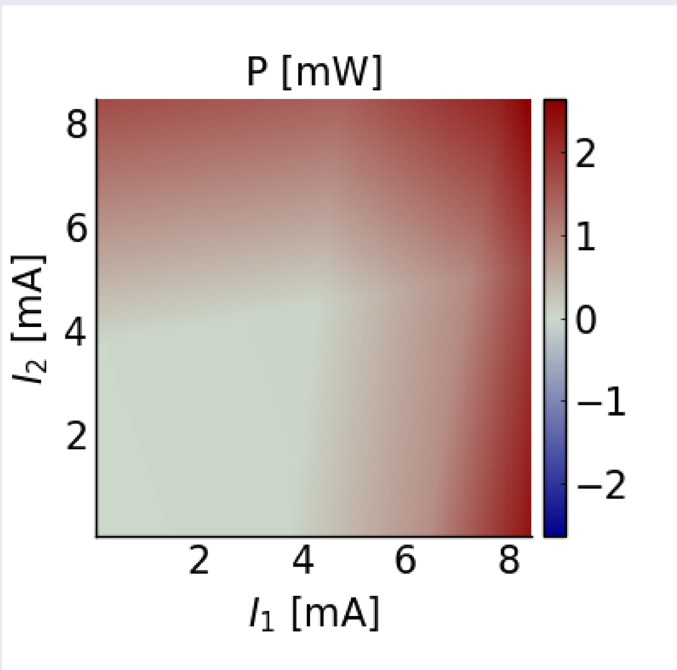


Naive estimate of coherent power enhancement

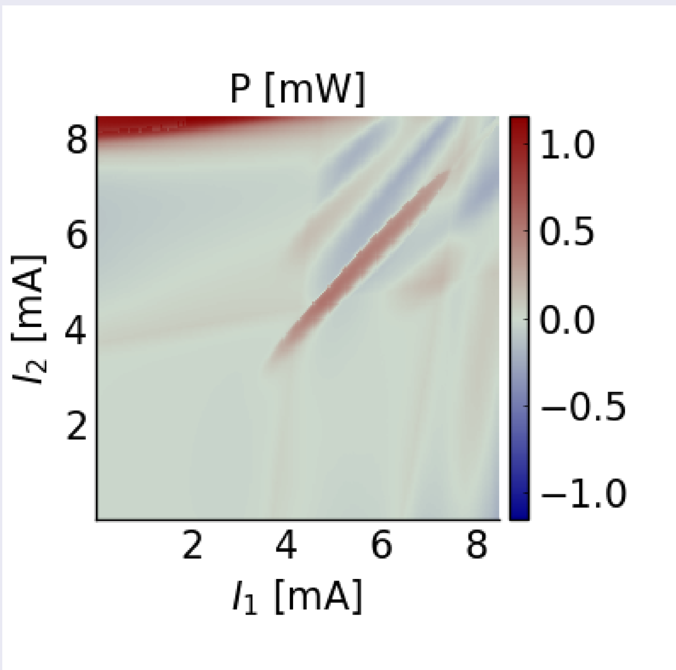
Machine Learning (ML) Approach

- Use artificial neural network (ANN) to infer the optical array power from the driving currents
- Train to minimize mean-square-error between measured and inferred power
- Coherent datapoints in training (measurement) dataset will induce error
- Use a two-pass approach:
  1. Train ANN on full measurement dataset
  2. Identify likely coherent datapoints (measurements with much more power than ANN infers)
  3. Train ANN on reduced dataset (excluding likely coherent datapoints)

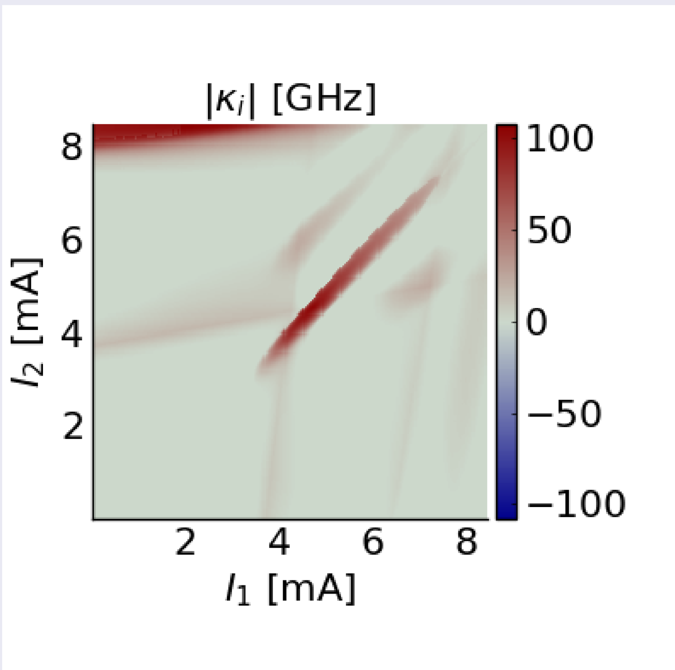
Results



ML estimate of uncoupled array power



ML estimate of coherent power enhancement



ML estimate of imaginary coupling coefficient

Conclusions

- Machine learning approach enables better estimate of coherent power enhancement than the "naive" approach
- A two-pass approach enables unsupervised learning while minimizing prediction error due to inclusion of coherent data
- Coherent power enhancement can help identify coherently coupled operation conditions and quantify coupling coefficient
- **Open source code available online [6, 7]**
- See the related talks:
  - *"Extraction of Coupling Coefficient for Coherent 2x1 VCSEL Array"* by Nusrat Jahan
  - *"Spectral Mode Analysis of Non-Hermitian Phased Microcavity Laser Array"* by William North

References

[1] H. Dave, Z. Gao, S. T. M. Fryslie, B. J. Thompson, and K. D. Choquette. Static and dynamic properties of coherently-coupled photonic-crystal vertical-cavity surface-emitting laser arrays. *IEEE Journal of Selected Topics in Quantum Electronics*, 25(6):1–8, November 2019. doi: 10.1109/jstqe.2019.2917551. URL https://doi.org/10.1109/jstqe.2019.2917551.

[2] H. Dave, P. Liao, S. T. M. Fryslie, Z. Gao, B. J. Thompson, Alan E. Willner, and K. D. Choquette. Digital modulation of coherently-coupled 2 × 1 vertical-cavity surface-emitting laser arrays. *IEEE Photonics Technology Letters*, 31(2):173–176, January 2019. doi: 10.1109/lpt.2018.2888806. URL https://doi.org/10.1109/lpt.2018.2888806.

[3] 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 2021. doi: 10.1117/12.2585066. URL https://doi.org/10.1117/12.2585066.

[4] H. Dave, Z. Gao, and K. Choquette. Complex coupling coefficient in laterally coupled microcavity laser diode arrays. *Applied Physics Letters*, 117(4):041106, July 2020. doi: 10.1063/5.0014468. URL https://doi.org/10.1063/5.0014468.

[5] S. T. M. Fryslie, M. T. Johnson, and K. D. Choquette. Coherence tuning in optically coupled phased vertical cavity laser arrays. *IEEE Journal of Quantum Electronics*, 51(11):1–6, November 2015. doi: 10.1109/jqe.2015.2481724. URL https://doi.org/10.1109/jqe.2015.2481724.

[6] Pawel Strzebonski. VCSELArrayAnalysis.jl, 2021. URL https://gitlab.com/pawelstrzebonski/VCSELArrayAnalysis.jl.

[7] Pawel Strzebonski. VCSELArrayAnalysisML.jl, 2021. URL https://gitlab.com/pawelstrzebonski/VCSELArrayAnalysisML.jl.