Computational Methods for VCSEL Array Characterization and Control

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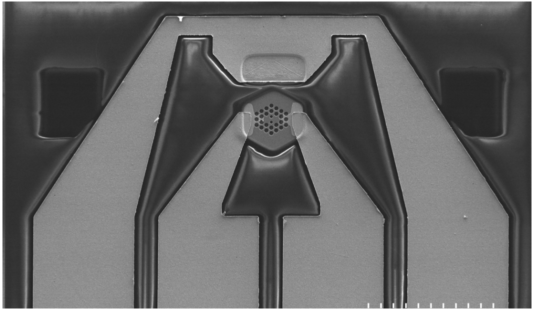
Motivation

- Why coherently coupled VCSEL arrays?
- Past work has shown:
    - Power enhancement (Dave et al. JSTQE 2019, Gao et al. APL 2019)
    - Reduced intensity noise and harmonic distortion (Dave et al. JSTQE 2019)
    - Enhanced small-signal modulation (Dave et al. PTL 2019)
    - Reduced divergence (Siriani et al. EL 2010)
    - Electrically controlled beam-steering (Johnson et al. JSTQE 2013)



Challenge and Goals

- Getting to coherent operation requires:
  - Array design
  - Fabrication and processing
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- Challenges:
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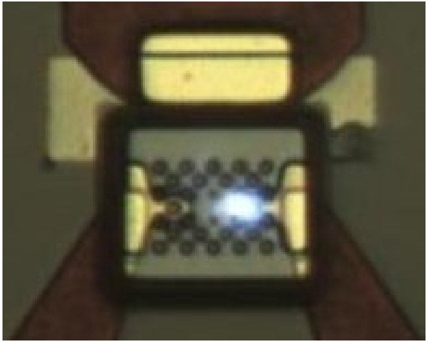
  - Repeat for wide range of potential operating conditions (exponential scaling with # of array elements)
- Goal is to develop computational methods:
  - For identifying coherence in measurement data,
  - That can be easily automated,
  - And can scale to large datasets and arrays

Background

- Photonic crystal, ion-implanted VCSELs
- Focus on 2×1 arrays
- Cavities are individually addressable
- I_1, I_2 are currents to individual cavities

Left element on



Right element on

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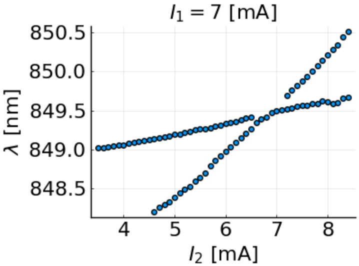
Optical Spectrum Analysis

- Coherent when both cavities lase at same wavelength (Thompson et al. PJ 2017, Dave et al. PTL 2019, Gao et al. APL 2019)
- Tuning driving currents tunes spectral peaks into each-other



Spectral peaks converge to single peak when coherent

Optical Spectrum Analysis

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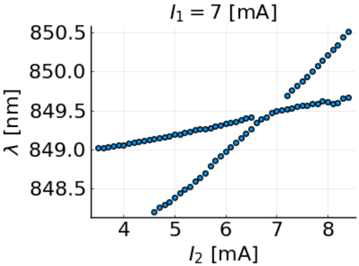
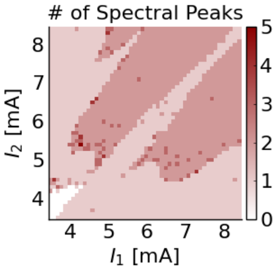
- Can count # of peaks at driving current to see potential coherent region



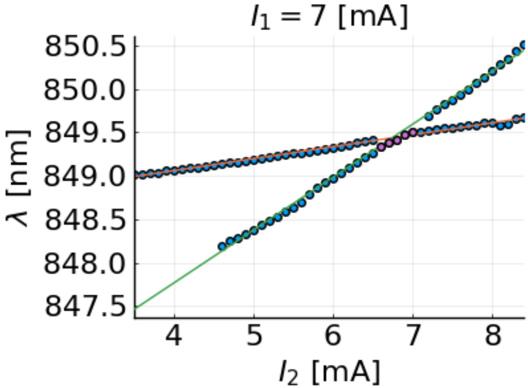
Spectral peaks converge to single peak when coherent



Tuning into coherence give single spectral peak from 2-element array

Optical Spectrum Analysis

- Optical spectrum measurements are relatively slow
- Can we do more with less data?
- Modeling spectral mode evolution enables prediction of coherent region (intersections)
- Use RANSAC to iteratively find/fit linear features in spectral mode data (Fischler et al. ACM 1981)
  1. Pick random subset of points
  2. Linear fit to subset
  3. Count total # of points close to linear fit
  4. If enough points are fitted, accepted linear model as a mode and remove close points
  5. Repeat from step 1 with remaining points



Linearly fitting spectral peak position as function of current

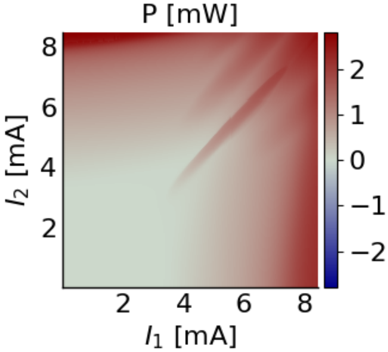
Optical Spectrum Analysis

Potential issues:

- Iterative, non-deterministic method
- Spectral modes may not be well represented using linear model
  - Try quadratic modeling?
- Intersections may not necessarily be coherent regions:
  - Intersections may be beyond laser operating conditions
  - Intersections may be before/after a spectral mode exists
  - Must separately verify separate cavity modes exist in vicinity of intersection

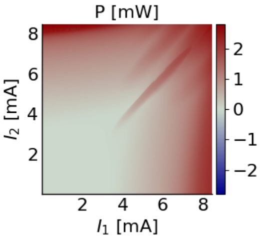
Optical Power Analysis

- Coherent coupled modes can have lower threshold than individual cavity modes
- May lead to lasing below individual cavity threshold, power enhancement (Dave et al. JSTQE 2019, Gao et al. APL 2019)
- Often shows as a "coherent ridge" in 2D current-power plots
- Power enhancement versus incoherent lasing could be used to detect coherence
- Strength of coherent power enhancement related to magnitude of imaginary coupling coefficient (Dave et al. JSTQE 2019, Gao et al. APL 2019)
- Can we calculate coherent power enhancement?

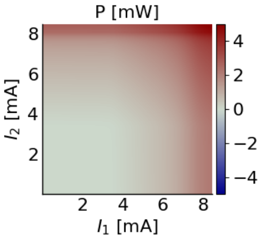


Optical Power Analysis

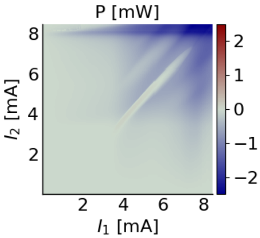
- Try to estimate uncoupled power using power-current curves for individual cavities
- Approach fails due to thermal shifting of power-current curves



Measured power



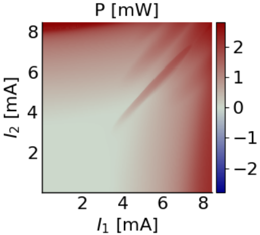
Uncoupled power



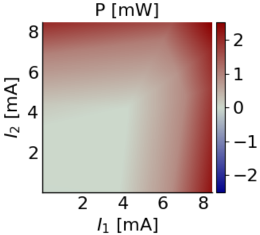
Coherent power enhancement

Optical Power Analysis

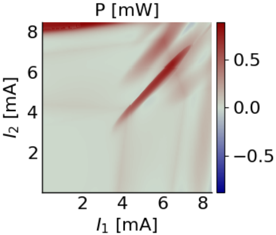
- Train simple artificial neural network to predict array power from driving currents ($[I_1, I_2] \rightarrow P$)
- Network will tend to predict uncoupled power well, coherent power not so well
- Can work well, but can be slow and finicky to train



Measured power



Uncoupled power



Coherent power enhancement

Optical Power Analysis

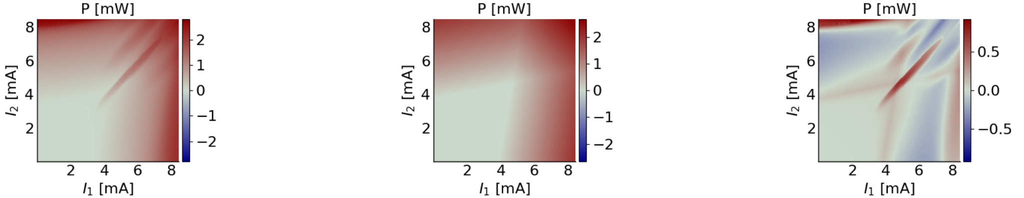
A better approach:

- Try analytical modeling of current-power behavior
- Define effective thermally shifting current for each cavity:
  $I_{\mathrm{i,shifted}}(I_1, I_2, \dots) = \sum_j \alpha_{ij} I_j$
- Define power in each cavity as rectified polynomial:
  $P_i(I_{\mathrm{i,shifted}}) \approx \max\left(\sum_{j=0}^{N} \beta_{ij} {I_{\mathrm{i,shifted}}}^j, 0\right)$
- Total array power is sum of cavity powers:
  $P = \sum_i P_i$
- Optimize coefficient values α_{ij}, β_{ij} to fit measured data

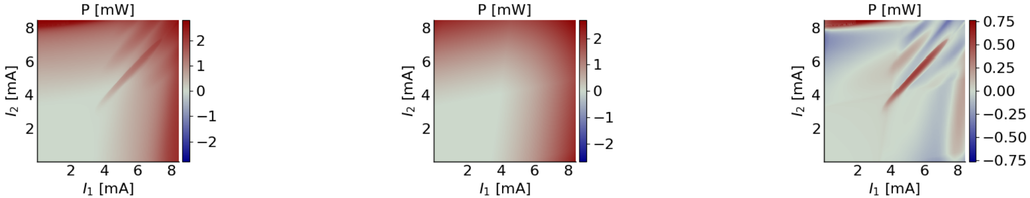
Optical Power Analysis

- Decent model performance and well behaved optimization versus neural network approach

Power | Uncoupled power | Coherent power enhancement



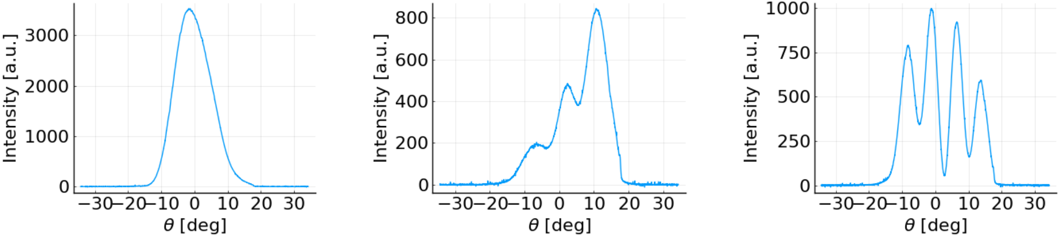
Linear cavity powers



Quadratic cavity powers

Far-Field Analysis

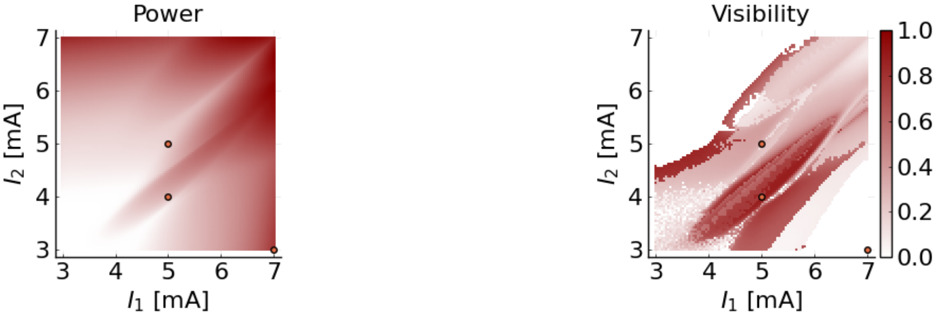
- When cavities are coherently coupled, their field interfere in the far-field (Dave et al. JSTQE 2019, Dave et al. PTL 2019, Gao et al APL 2019)
- Strength of coherence can be inferred from strength of interference fringes



Far-fields for a 2 × 1 array, from low to high coherence

Far-Field Analysis

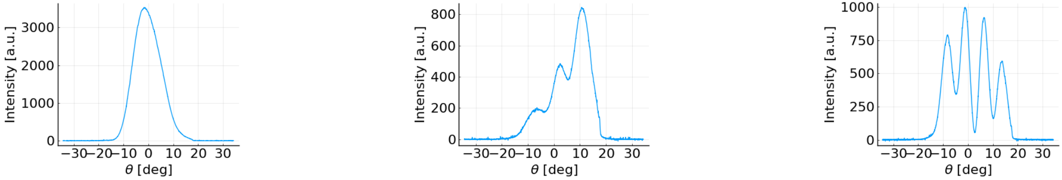
- Visibility parameter $V = \frac{\langle I_{max}\rangle - \langle I_{min}\rangle}{\langle I_{max}\rangle + \langle I_{min}\rangle}$ for peak/valley intensity I_{max}, I_{min} (Gao 2018 PhD Thesis, Dave 2019 PhD Thesis)
- Visibility proportional to coherence in 2×1 array of single-fundamental-mode VCSELs
- Ill-defined for more complicated arrays, tricky to calculate due to maxima/minima search



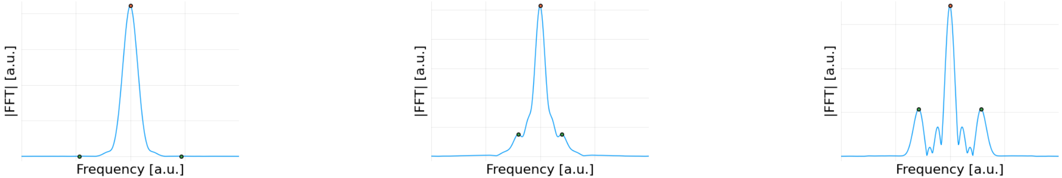
Note: Dots represent locations of previous far-field profiles

Far-Field Analysis

- Try calculating FFT of far-field
- Interference fringes show up as higher-frequency signals in FFT
- Can relative amplitude of side-peak to 0-frequency (central) peak infer coherence?



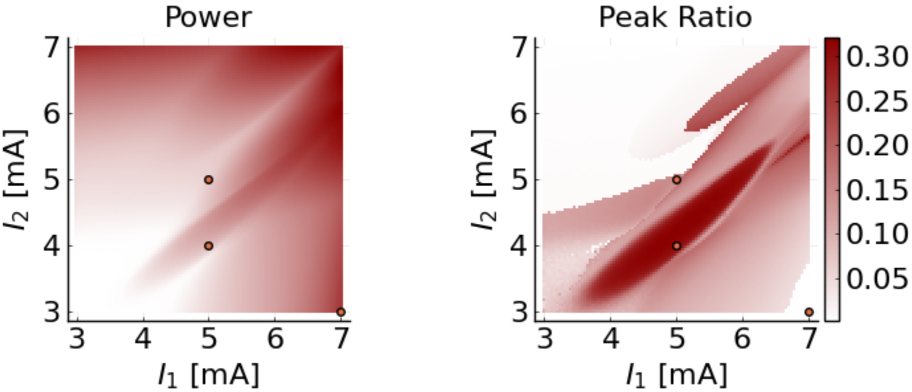
Far-fields



FFTs of far-fields

Far-Field Analysis

- Plot ratio of amplitudes for side-peak to central 0-frequency peak
- Simpler to calculate, may extend better to more complicated arrays and 2D far-field images than visibility



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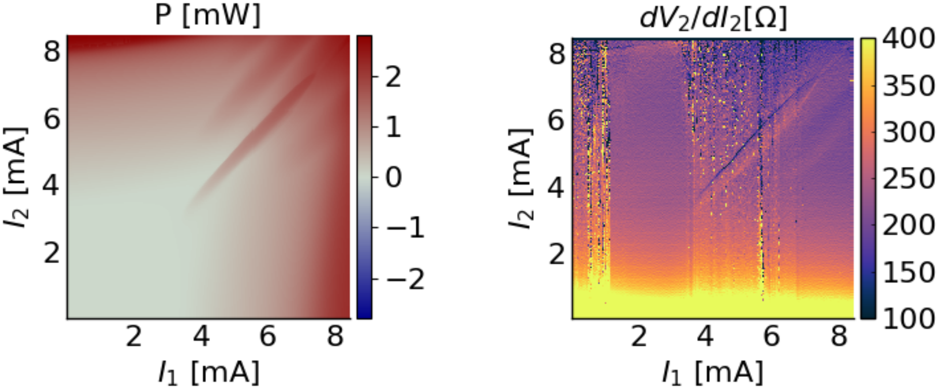
Differential Resistance Analysis

- Entering/exiting coherent operation changes differential resistance (Dave et al. IPC 2019)
- Voltage derivative can show features at edges of coherent ridge
- Data tends to be noisy, even after preprocessing



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Conclusions

- VCSEL array coherence analyzed using various measurements and analysis methods
- Optical spectra:
  - Effective and potentially predictive
  - Slow, not integrable
- Optical power:
  - Simple, reasonably fast, effective, and integrable
- Far-fields:
  - Effective
  - More setup, not too integrable
- Differential resistance:
  - Very simple, integrable, and fast
  - Currently impractical due to noise
- Future work involves scaling to larger arrays