Robustness of Injection Steering for Semiconductor Laser Arrays

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Motivation

Coupled VCSEL arrays exhibit multiple phase-locked steady states, making them promising for controllable photonic systems. However, in experiments, the array typically begins in a free-running state, so a practical control mechanism is needed to reliably transition the system to a desired locked equilibrium.

In this work, we study **injection steering**: a temporary optical injection pulse designed to move the array from free-running operation into a selected phase-locked state. After the pulse is removed, the array remains in the target equilibrium if that state is stable. Similar injection pulses have been used in [1, 2, 3, 4], but a comprehensive study of this phenomenon is yet to be published and we also test the robustness with respect to the number of lasers and correlated noise.

Objectives

- Demonstrate effectiveness for **more than two lasers**,
- Demonstrate robustness over a range of **injection profile parameters**, and
- Demonstrate resilience in the presence of **correlated noise**.

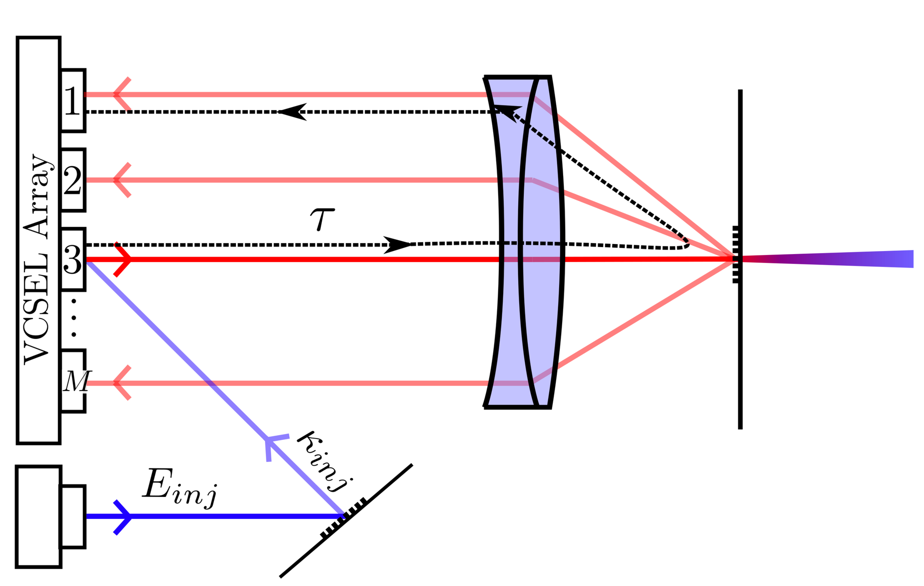


Figure 1. Injection steering schematic diagram showing the mutually coupled VCSEL array and the injection laser pulse steering the array to the frequency of the injection laser.

Model and Steering Method

We consider delay-coupled VCSEL rate equations with carrier, photon, and phase dynamics for each laser [5]. The steering signal is applied as a temporary external injection with tunable profile parameters such as amplitude, duration, frequency offset, and phase.

$$\begin{aligned}\frac{dN_i}{dt} &= \frac{\eta I}{q} - \frac{N_i}{\tau_n} - g_0\frac{N_i - N_0}{1+\gamma|E_i|^2}|E_i|^2 + F_{N_i}(t),\\ \frac{dE_i}{dt} &= \left[\frac{1}{2}\left(g_0\frac{N_i - N_0}{1+\gamma|E_i|^2} - \frac{1}{\tau_p} + \frac{\beta N_i}{\tau_n|E_i|^2}\right) + i\left(\frac{\alpha}{2}g_0\frac{N_i - \bar{N}}{1+\gamma|E_i|^2} + \delta_i\right)\right]E_i \\ &\quad + \sum_{j=1}^{M}\kappa_{ij}E_j(t-\tau)e^{-i\phi_p} + \kappa_{\text{inj}}(t)E^i_{\text{inj}}(t) + F_{E_i}(t),\end{aligned} \tag{1}$$

where $E^i_{inj}(t) = \sqrt{S_{inj}}e^{i(\omega_{inj}t+\phi_{inj})}$ and $\kappa_{inj}(t) = \kappa_{inj}\exp\left(-\frac{(t-t_p)^2}{2\tau_w^2}\right)$.

Conceptually, the procedure is

1. Initialize the array in a free-running state.
2. Apply a Gaussian injection pulse matched to the target equilibrium frequency.
3. Test whether the array settles into and remains at the desired state.

Injection Profile Parameter Study: 3 Lasers

To test scalability beyond the two-laser case, we perform parameter sweeps for a **3-laser array** over the injection profile.

- We tested injection profiles with $\kappa_{inj} \in [0, 50\kappa_c]$ and $\tau_w \in [0, 10\tau]$.
- Varied $\kappa_c \in [0, 40]\ ns^{-1}$ and $\delta \in [0, 5]\ GHz$.
- Computed the average and standard deviation distance from desired frequency.

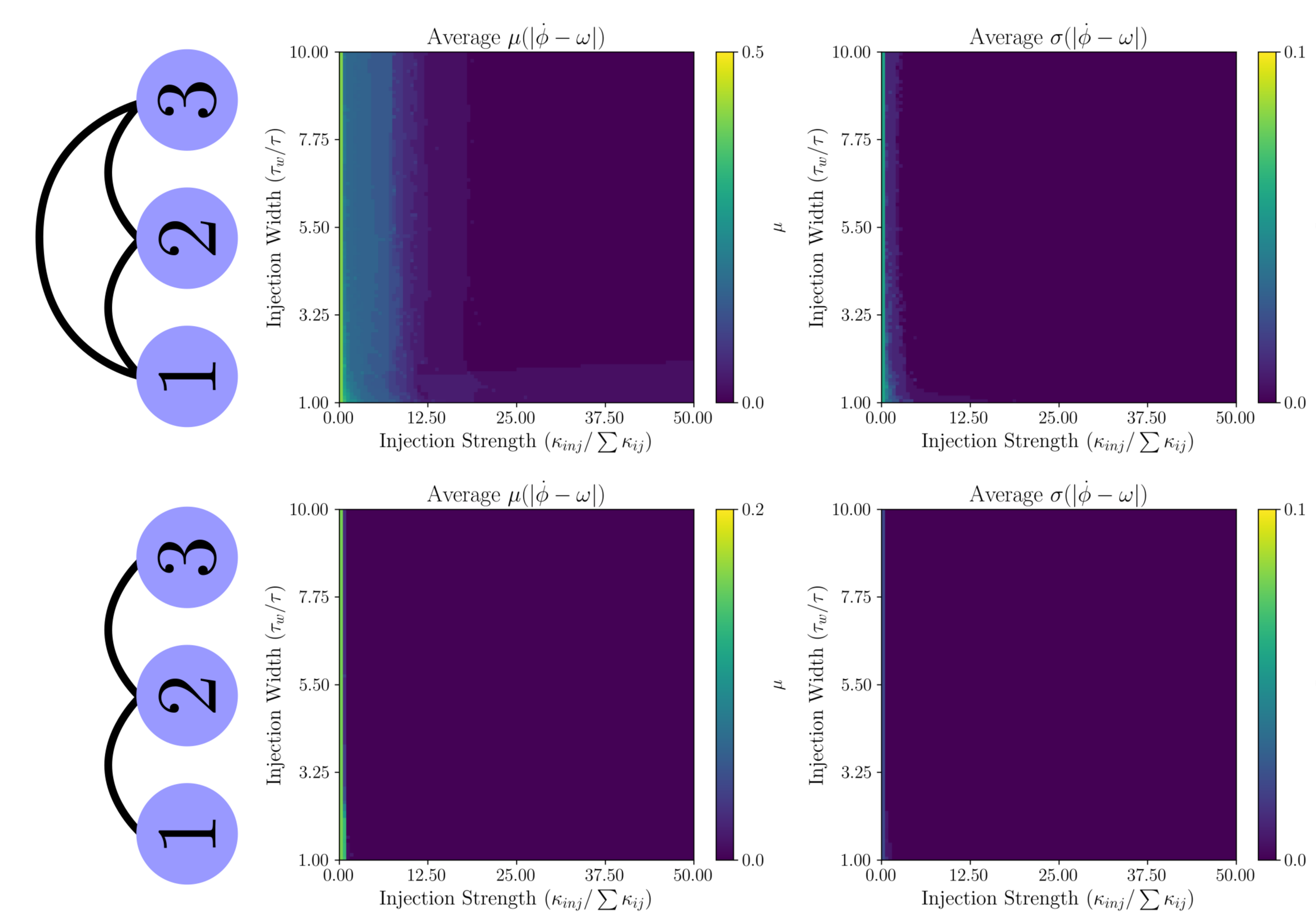
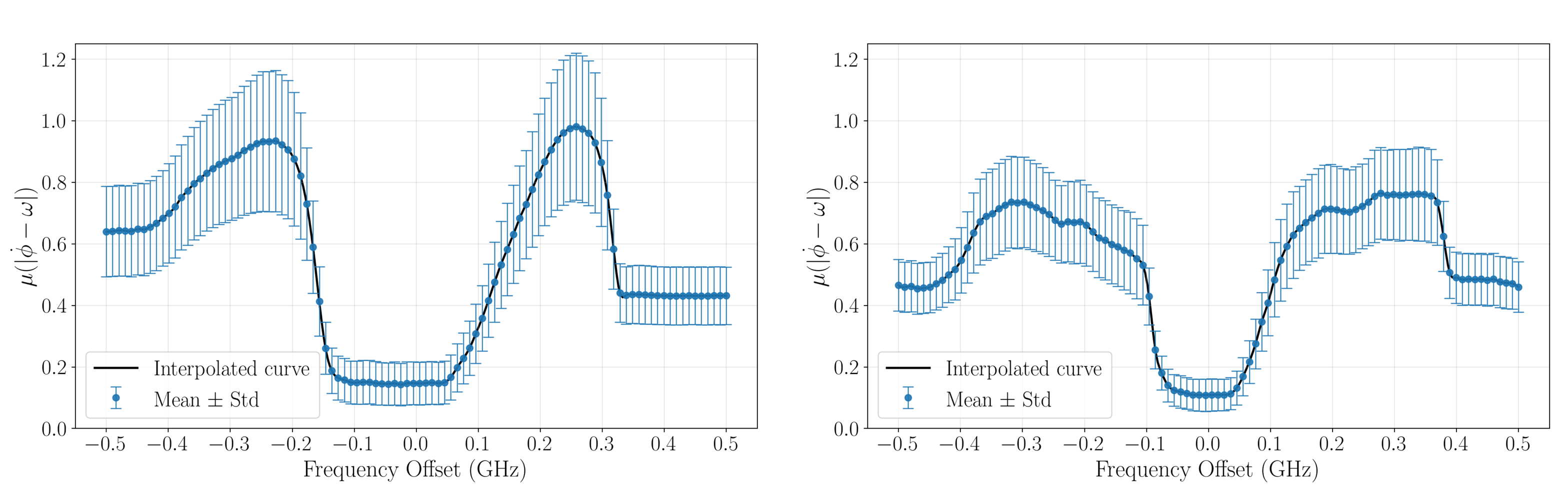


Figure 2. Test results varying the injection steering pulse strength and width over many different coupling strengths and detuning frequencies for a three laser array.

Noise Robustness

Correlated Langevin noise [5, 6] was included to test robustness in both **2-laser** and **3-laser** systems. The noise is correlated due to interactions between photons and carriers in the cavity. To test the robustness to noise, we tested two and three laser arrays over $\kappa_c \in [0, 40]\ ns^{-1}$ and $\delta \in [0, 5]\ GHz$ each with 100 noise iterations and random coupling topology for the three laser system. For each simulation we attempted to steer the system to the equilibrium with a frequency that was offset by some amount from the true equilibrium.



(a) Two Laser Array (b) Three Laser Array

Figure 3. Noise robustness test over 100 noise iterations to measure the mean and standard deviation distance from the target frequency with noise.

- Injection steering is robust to deviations in the frequency by about 0.1 GHz.
- On average the distance to the CLM frequency is approximately 0.1 GHz which is due to the top equilibrium being unstable for some coupling strengths (see Fig. 5).

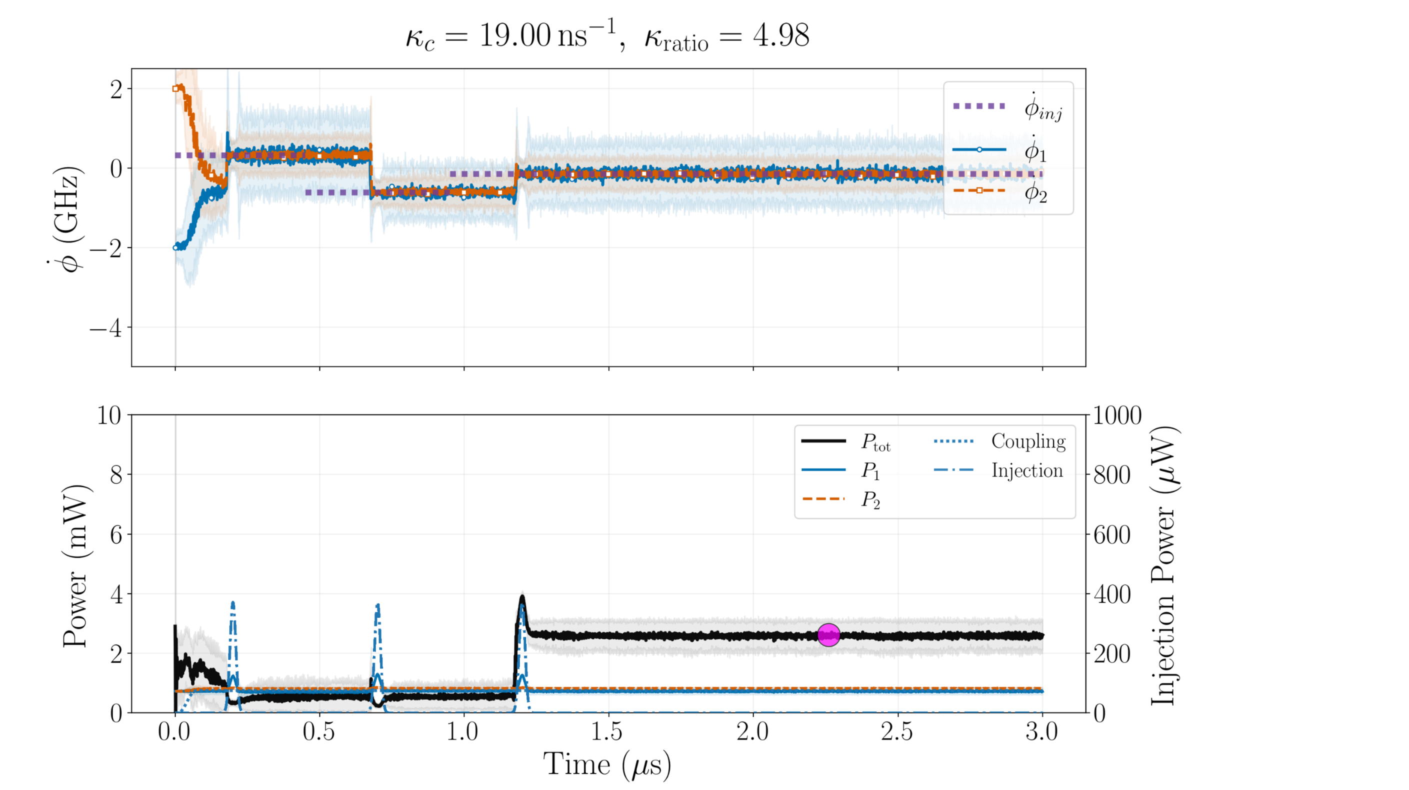


Figure 4. Two laser injection steering time domain example with noise at $\kappa_c = 19\ ns^{-1}$. Injection pulses are used to steer the system to all three stable equilibria.

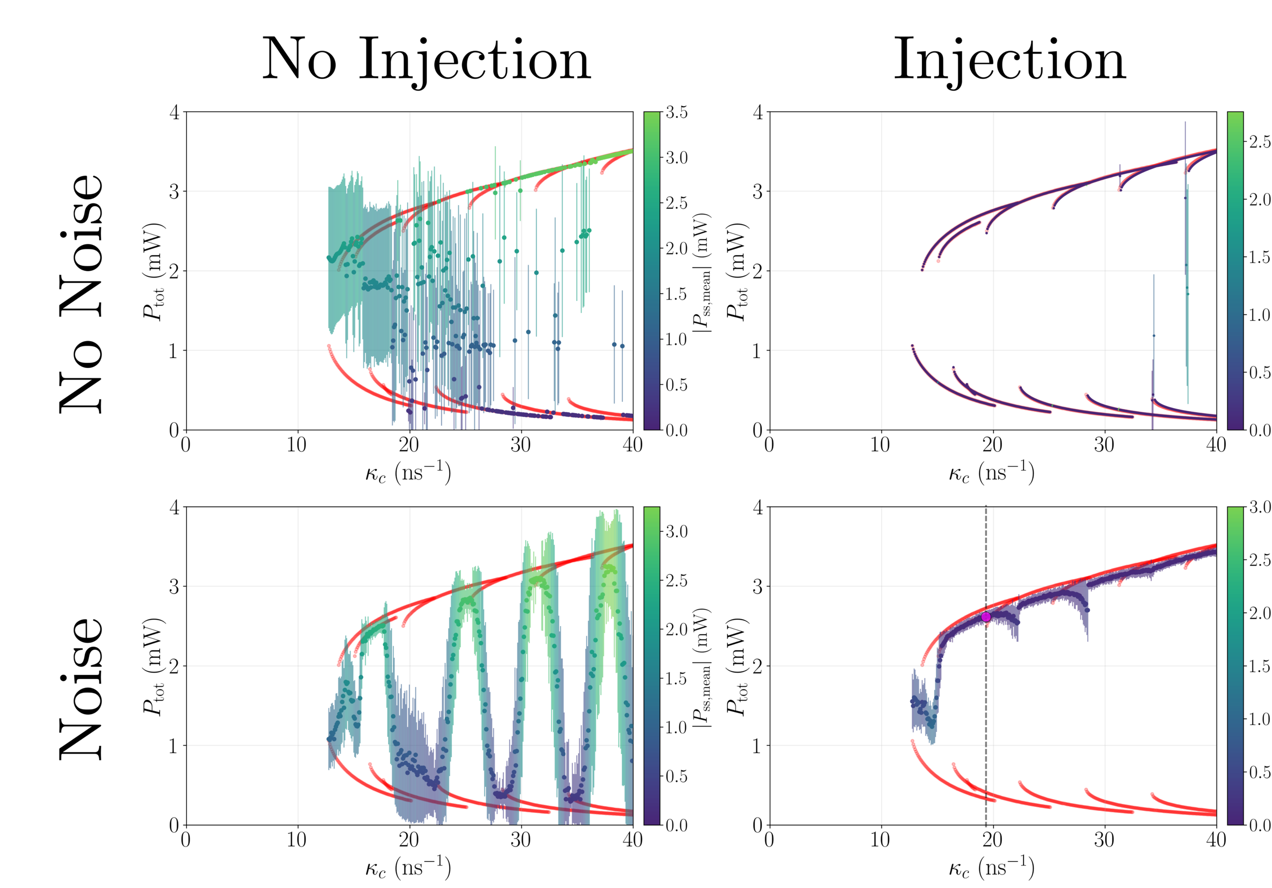


Figure 5. Steady state manifolds for a two laser system detuned by 4 GHz with and without noise. These manifolds were computed with and without injection steering enabled to demonstrate its effectiveness in steering the system to the desired fixed points.

Conclusions and Future Work

- Injection steering works beyond 2 lasers.
- Robust to correlated noise, but noise can destabilize equilibria.
- Test with larger arrays
- ML optimized pulse design to reach other dynamical states.

References

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