Synchronization of Broad-Area Semiconductor Laser Array

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Outline

- Coherent beam coupling
  - Incoherent beam addition and coherent beam coupling
  - Synchronization of multiple lasers for coherent coupling
- Experiments on synchronization of broad-area semiconductor lasers
  - Spectral/spatial properties
  - Coherence of injection-locked lasers
  - Temporal dynamics
  - Amplification of injection signal
- Nonmonotonicity and transient behavior in coupled lasers
- Concluding remarks

Synchronization

$$\mathrm{E}_j(t) = E_j \exp(-i\omega_j t) + cc$$

$$I(t) = \left| \sqrt{I_1}\exp(i\phi_1) + \sqrt{I_2}\exp(i\phi_2) + \ldots \right|^2$$

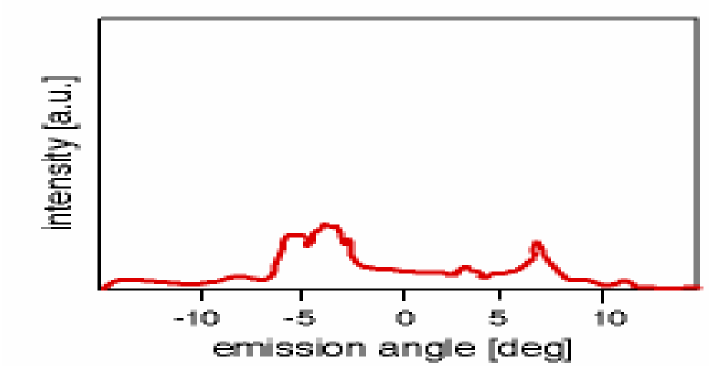
E_j - complex amplitude

ω_j - the frequency

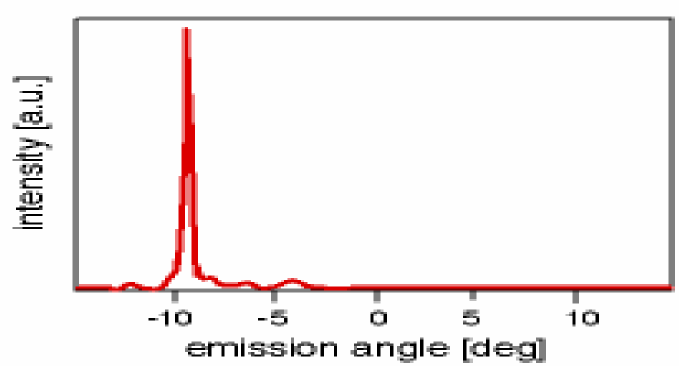
$$E_j = \sqrt{I_j}\, e^{i\phi j}$$

"in-phase" $\rightarrow \phi_1 = \phi_2 = \ldots = \phi_N$

$\Rightarrow I \sim N^2 I_0$

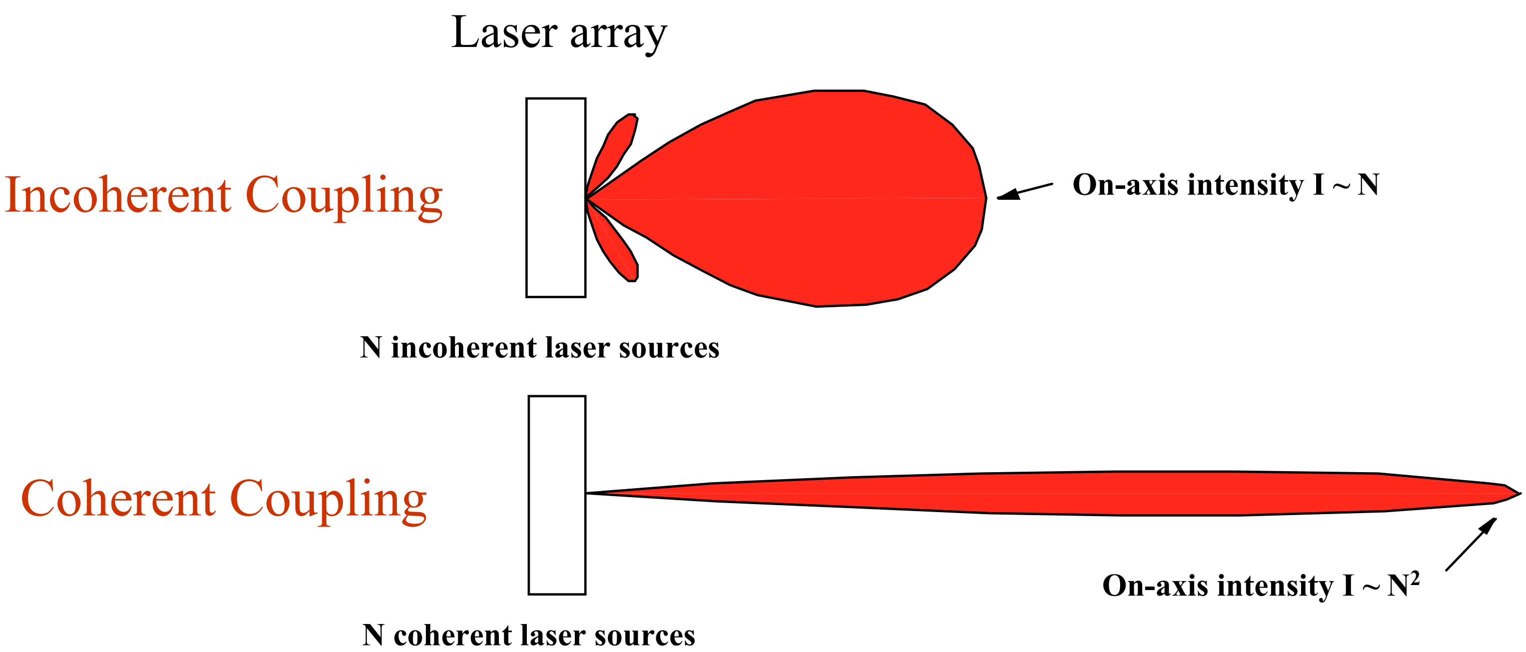


Noncoherent addition



Coherent addition

Coherent Beam Coupling of Laser Array



Applications:

Space Communications, Material Processing, Directed Energy

Our Research: Synchronization of laser array for coherent beam coupling

Conditions for coherent beam coupling

–Frequency locking

–Phase locking

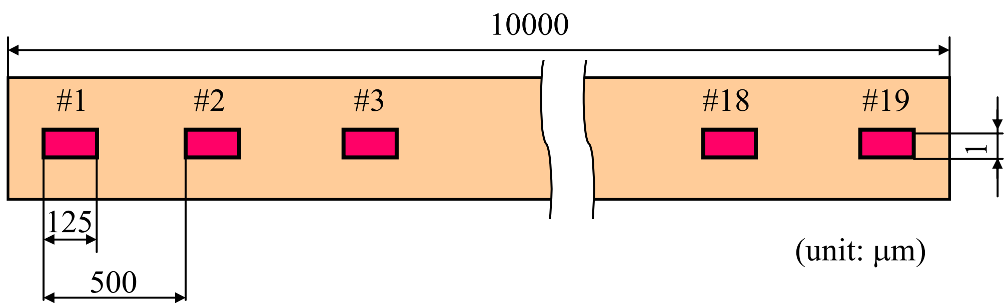
Laser array synchronization

–Scalability to high power

–Maintaining high coherence and high beam quality

–Cost effective

Broad-Area Semiconductor Laser Array



Maximum power: >1W (each laser)

Far-field angle: ~ 6×50°

Wavelength: 806~810 nm

Linewidth: ~ 2 nm

Experiments on Broad-Area Lasers

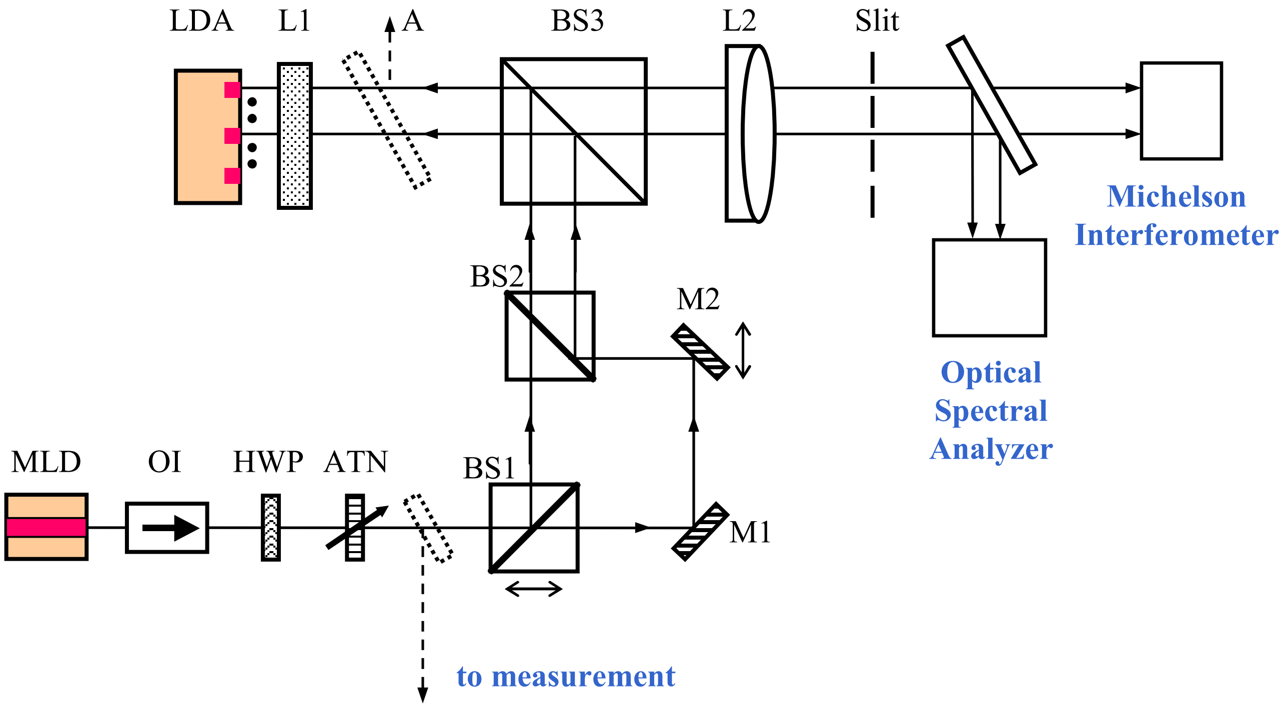
Single Broad-Area Laser Diode — aperture < 100 μm ×1 μm, power: < 1 W

Laser Array — overall array aperture < 100 μm ×1 μm
total output power < 1.2W

Our Objective

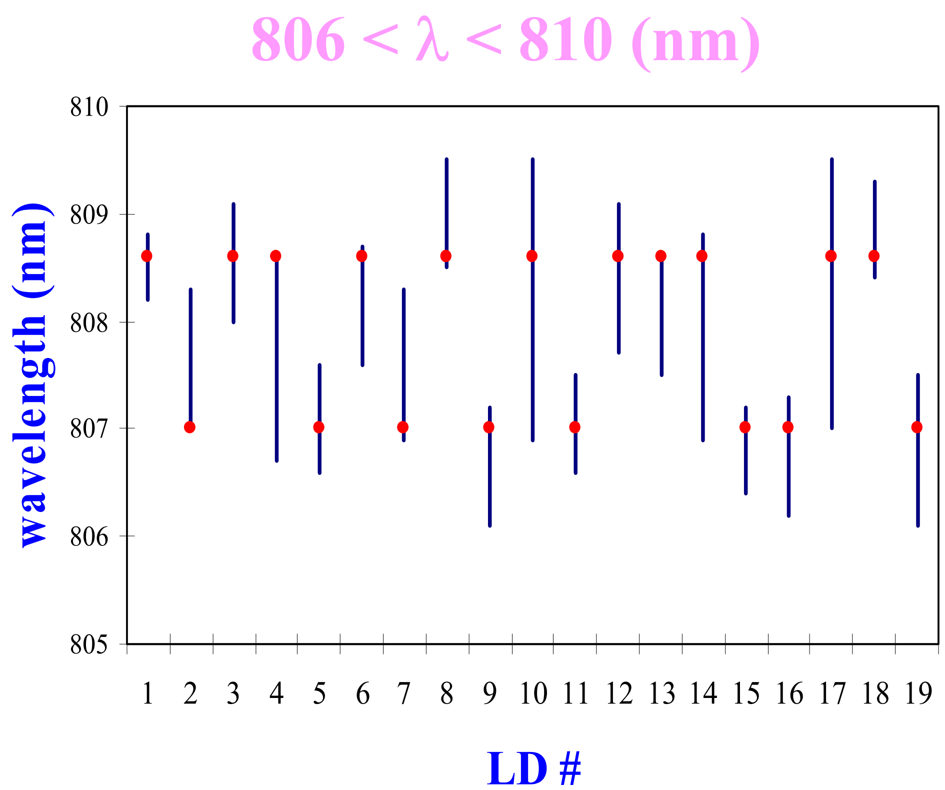
Synchronization and coherent coupling of a broad-area laser array

Experimental Setup of Injection Locking



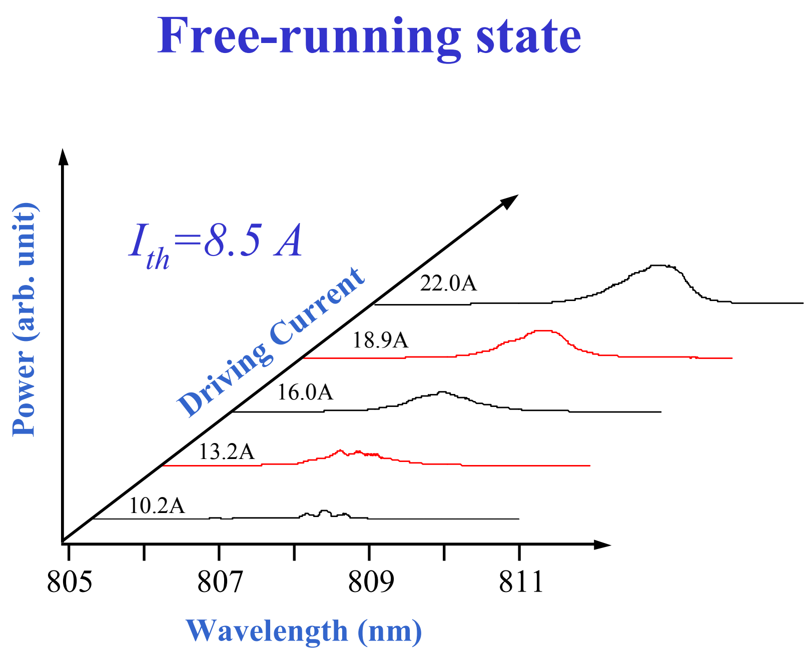
- Separate Injection Access to each Laser
- Ability to Split and Control Injection

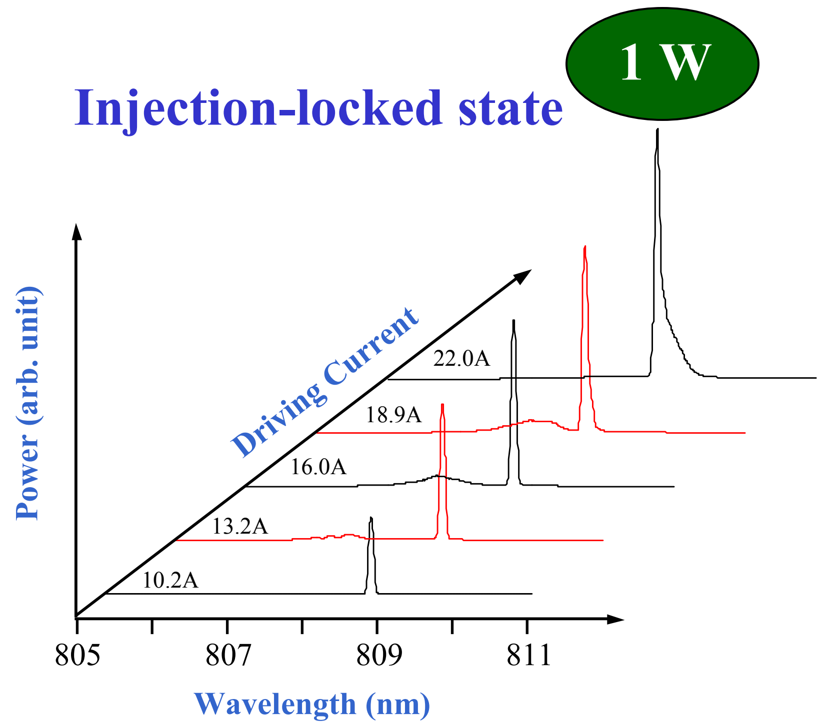
Wavelength Span of all 19 Lasers



● : **injection locking frequency around the driving current $I_d \sim 1.5\ I_{th}$**

Frequency Matching for Injection Locking



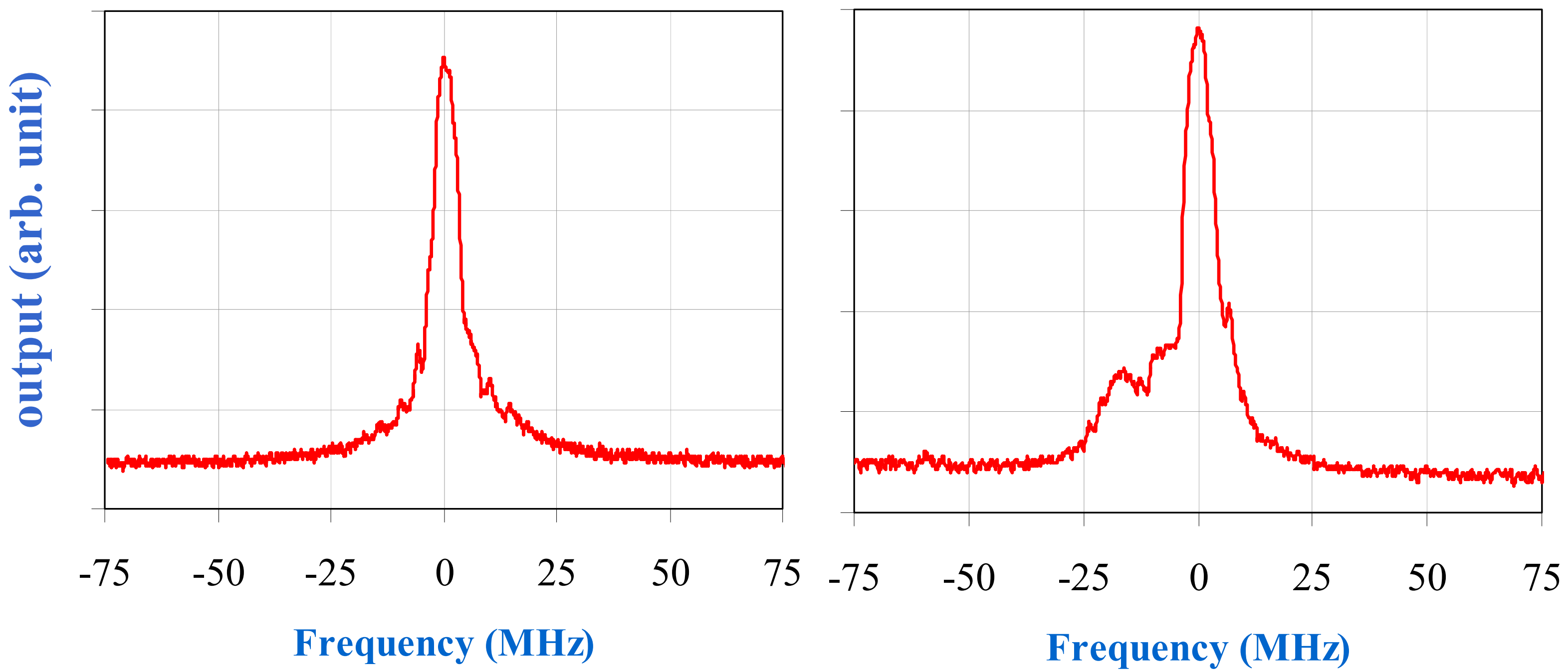


Condition for Injection Locking

- **Matching Between the Injection and Slave Laser Frequencies**
- **Less than 5 mW of Injection Power !**

Y. Liu, H. K. Liu, and Y. Braiman, *Appl. Phys. Lett.* 81, No.6 (2002)

Narrow Line Width of Injection-Locked Lasers



I_d=11.2A

I_d=22.0 A

Spectrum Bandwidth of the Order of 10 MHz

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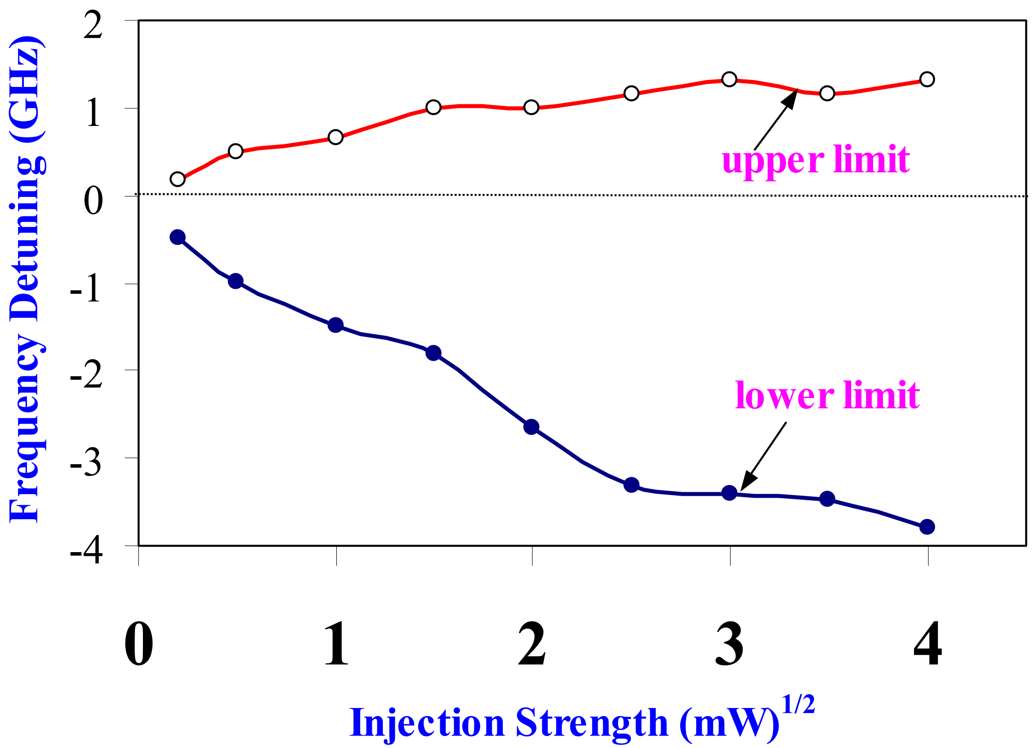
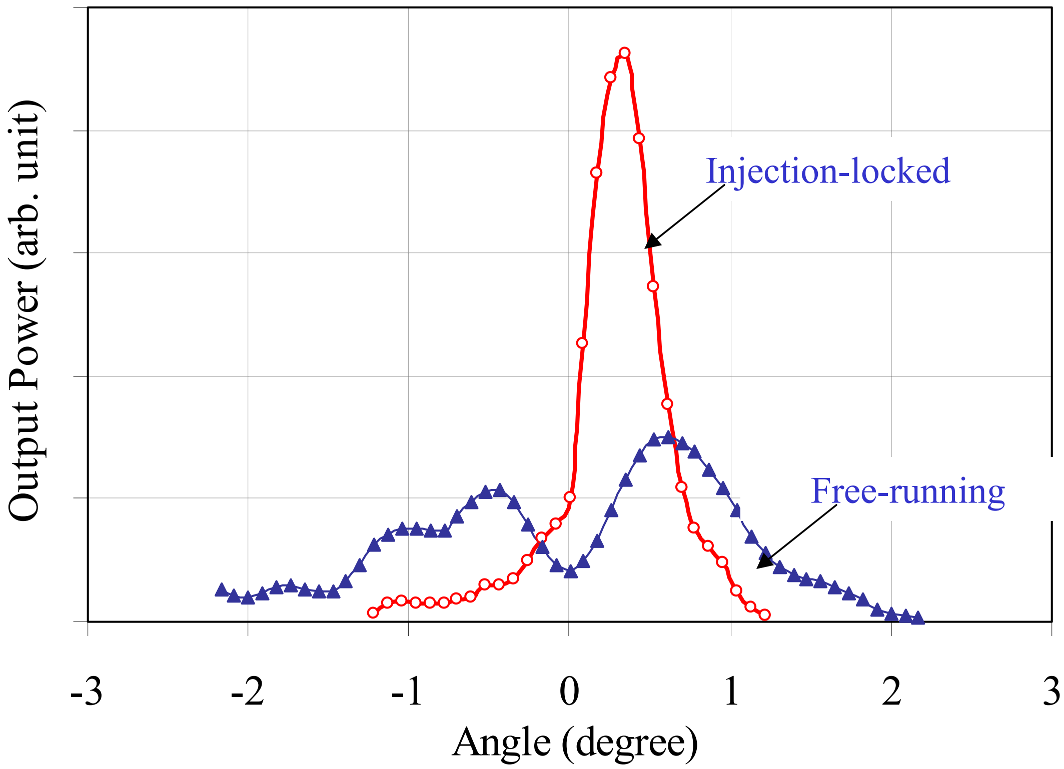
Injection Locking Range



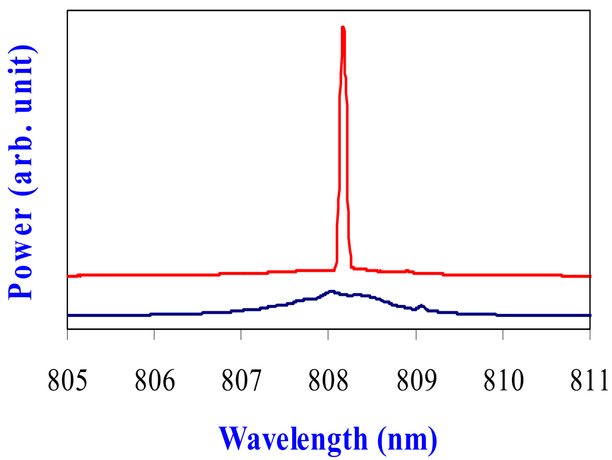
- Stable Locking Range
- At Low Drive Current, the Frequency Range for Stable Locking is Linear with the Injection Strength

Far-Field Pattern at Injection-Locking

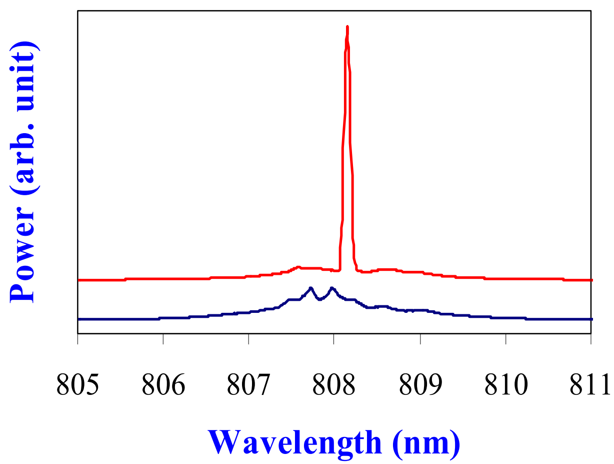


Far-field angle after injection locking: 0.4º (close to the diffraction limit from a 125-mm-wide emitting region

Simultaneous Injection Locking of Two Lasers



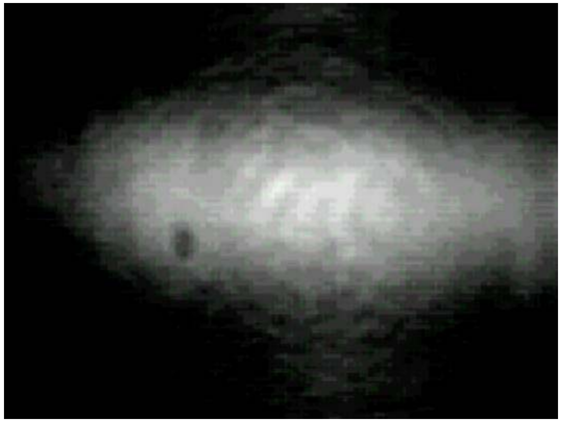
LD#7



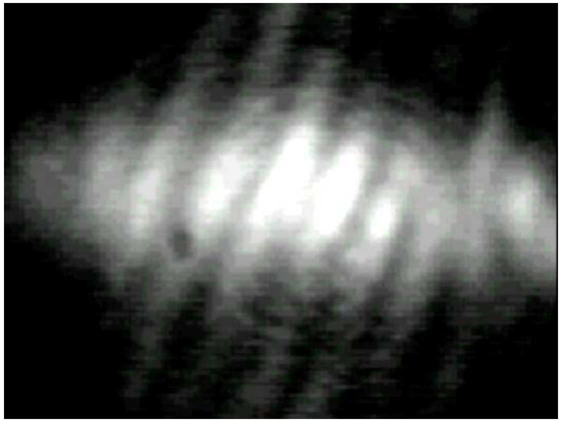
LD#12

- Equally Split Injection Power into Two Lasers
- Control the Strength of Injection

Interference Between Injection-Locked Lasers



Before Injection Locking

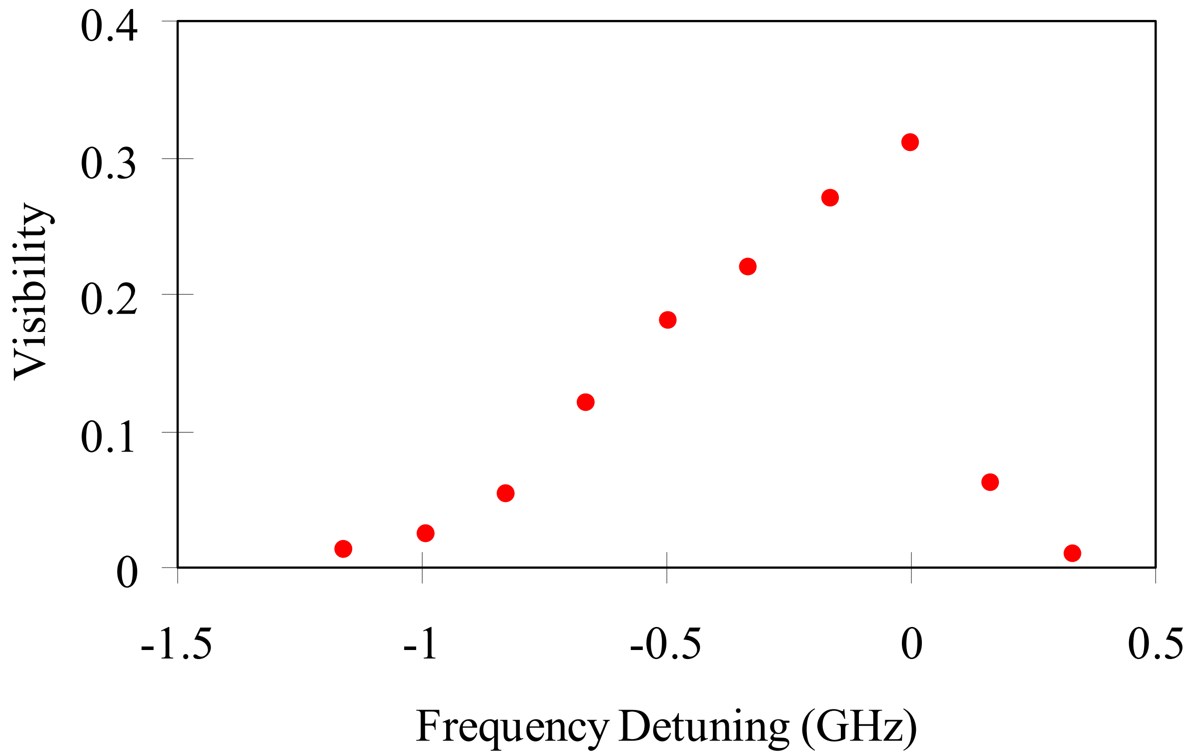


After Injection Locking

Stable Phase Relationship Between Lasers
Locking of Spatial Modes

Y. Liu, H. K. Liu, and Y. Braiman, *Applied Optics LP* 41 (2002)

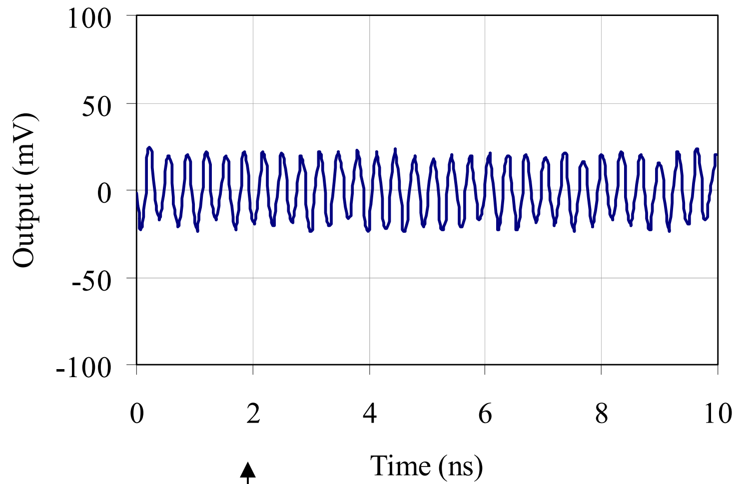
Parameter Dependence



Sensitive dependence of simultaneous injection locking on frequency matching

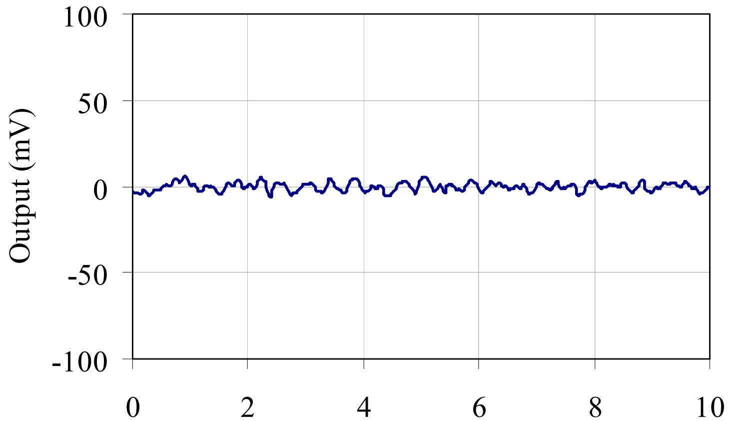
Temporal Dynamics

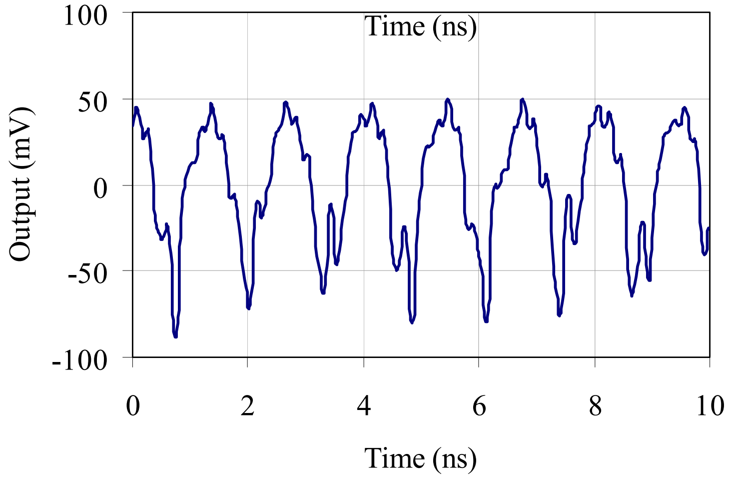
Free-running state



Relaxation oscillations (~3GHz)

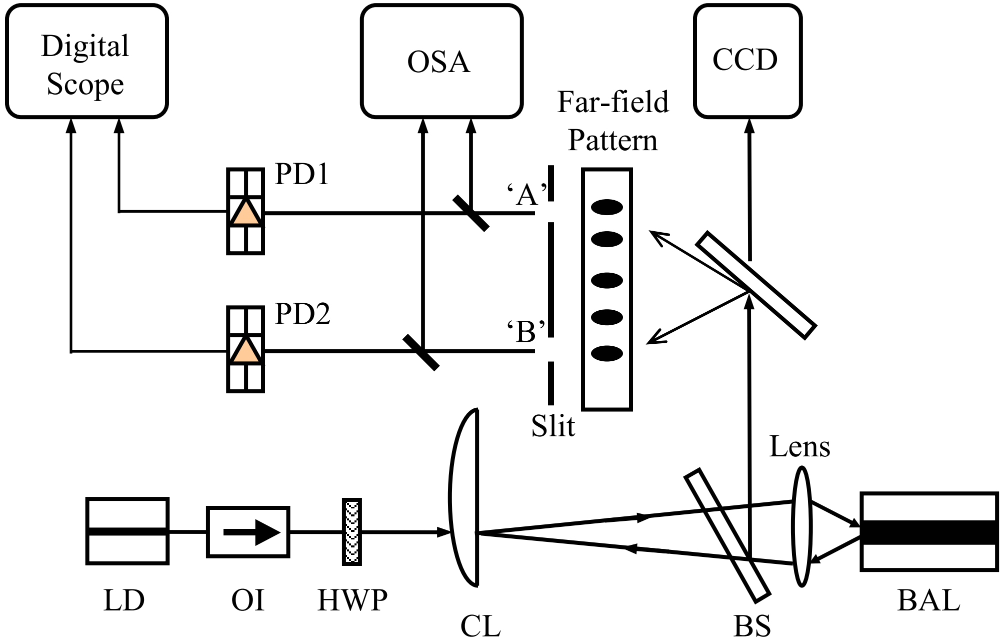
Injection-locked states





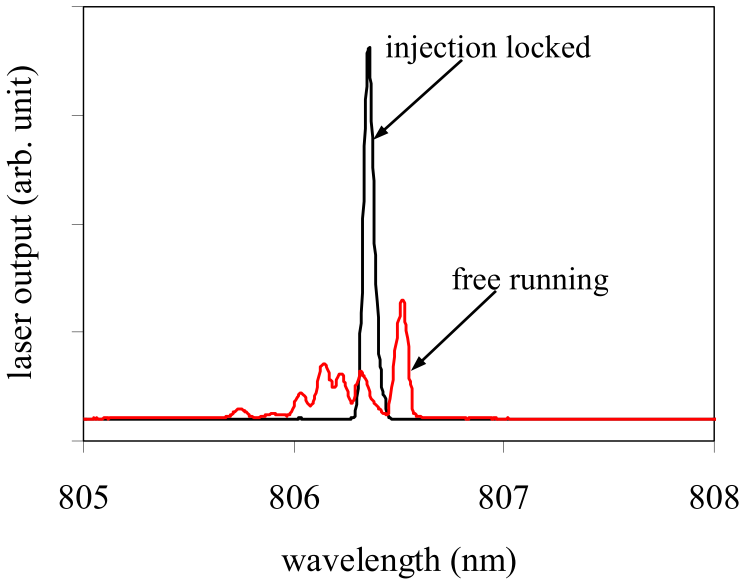
Bistability between stabilized state and low-frequency (~700 MHz) oscillation state

Spatial-Temporal Dynamics

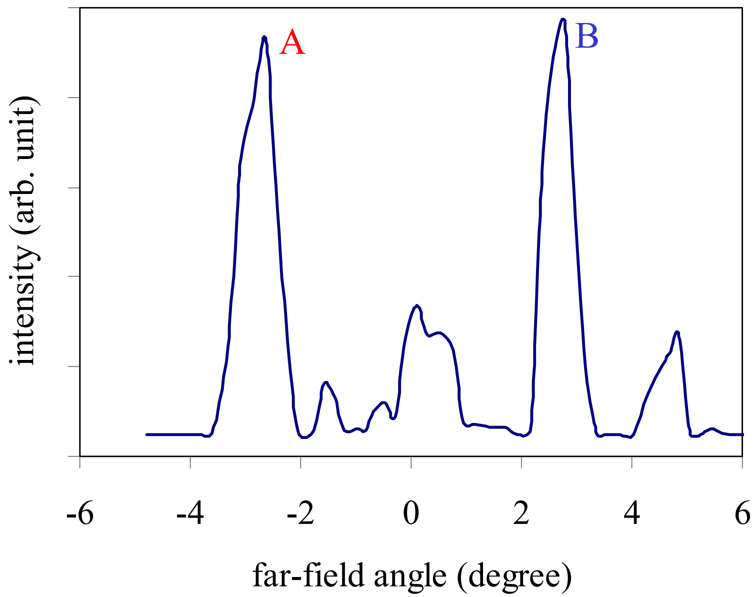


Experimental Setup of Measuring Temporal Waveform of Different Spatial Modes

Optical Spectrum

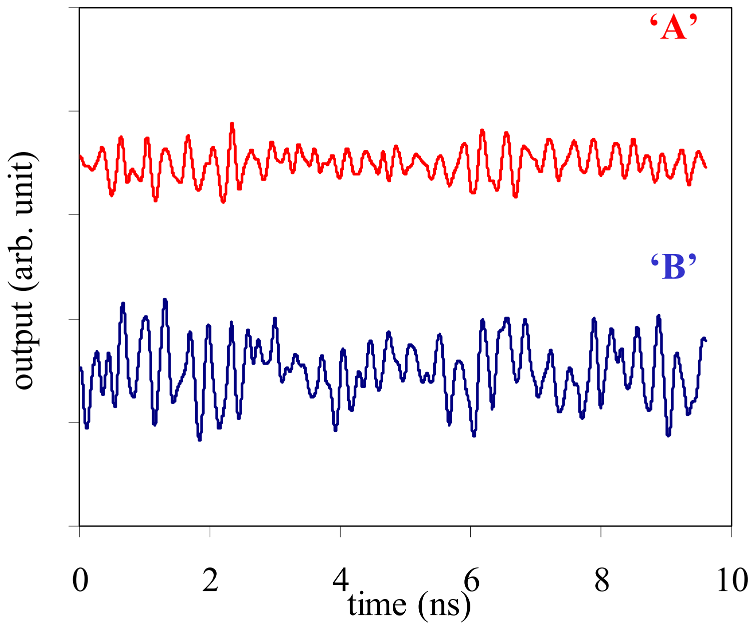


Far-Field Pattern

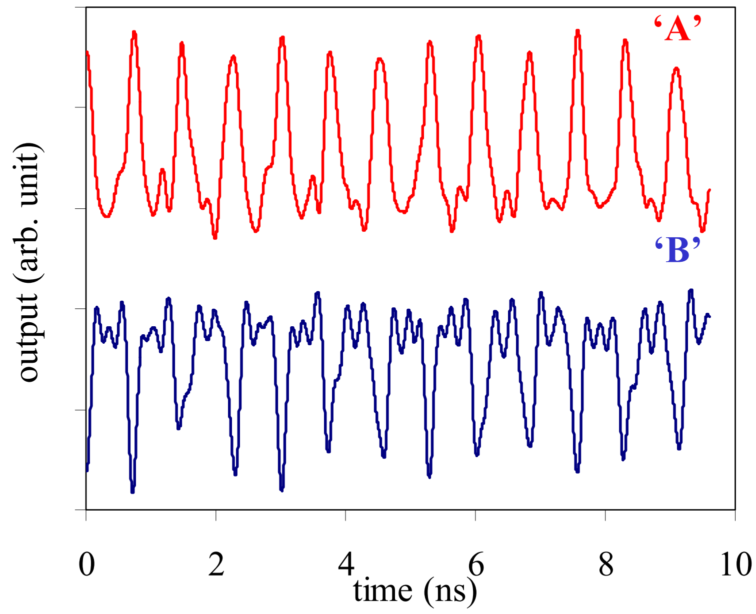


Temporal Dynamics of Different Spatial Modes

Free-Running



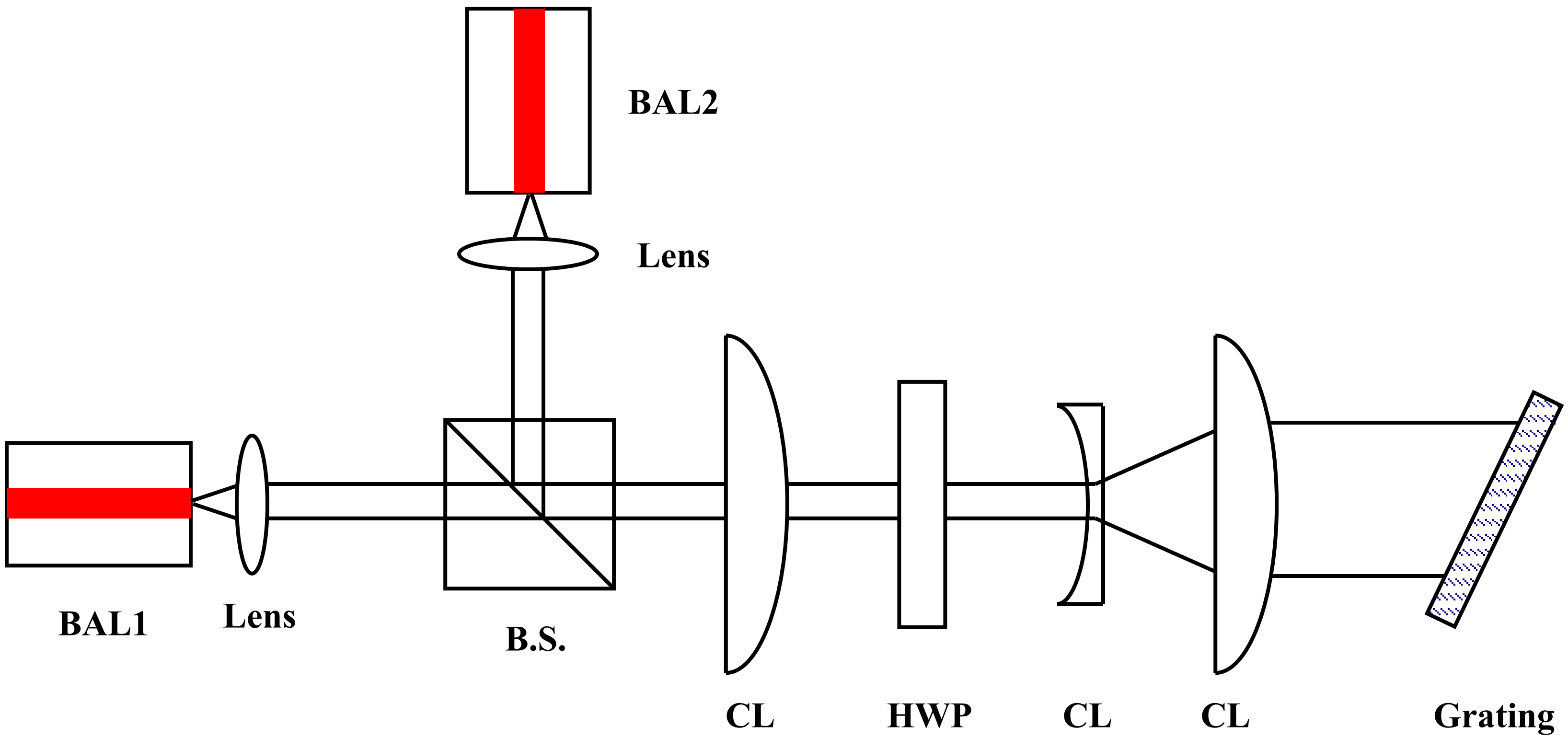
Injection Locked



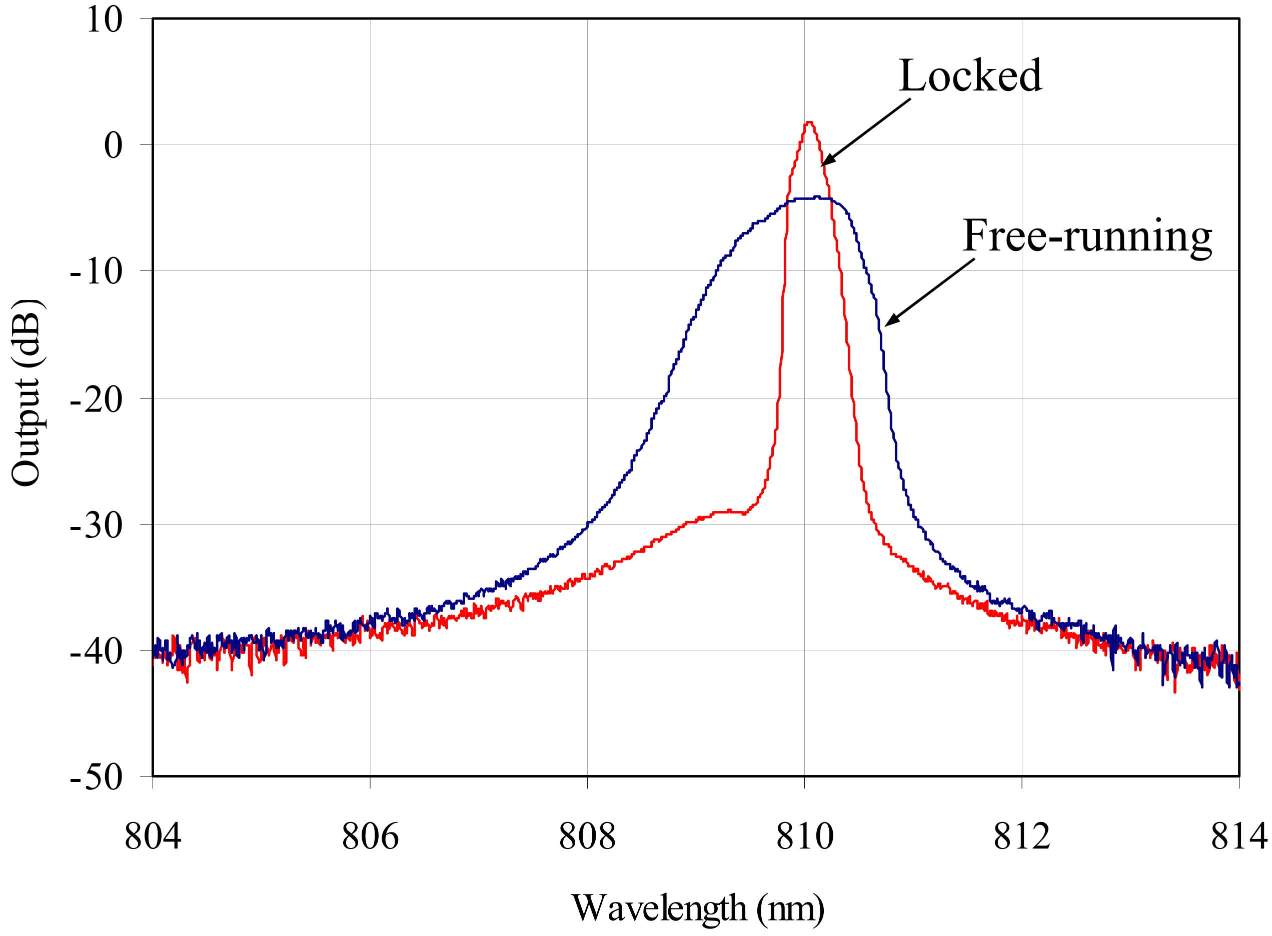
Experiment I

Self-injection Locking of Coupled Individual Broad-Area Lasers

Self-Injection Locking of Four Coupled Lasers

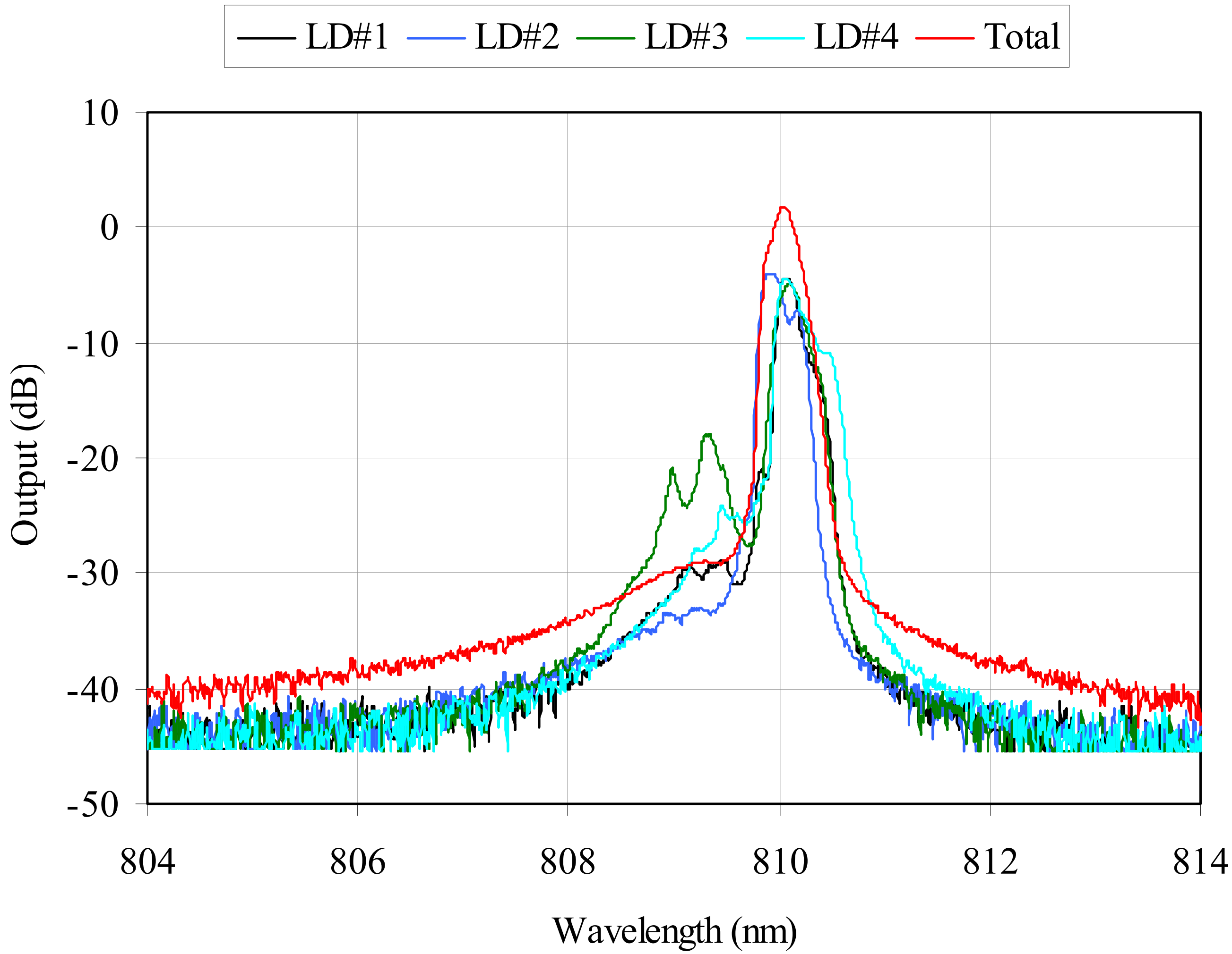


Self-Injection Locking of Four Coupled Lasers



Broad-Area Laser Array (0.9 W of power from each laser)

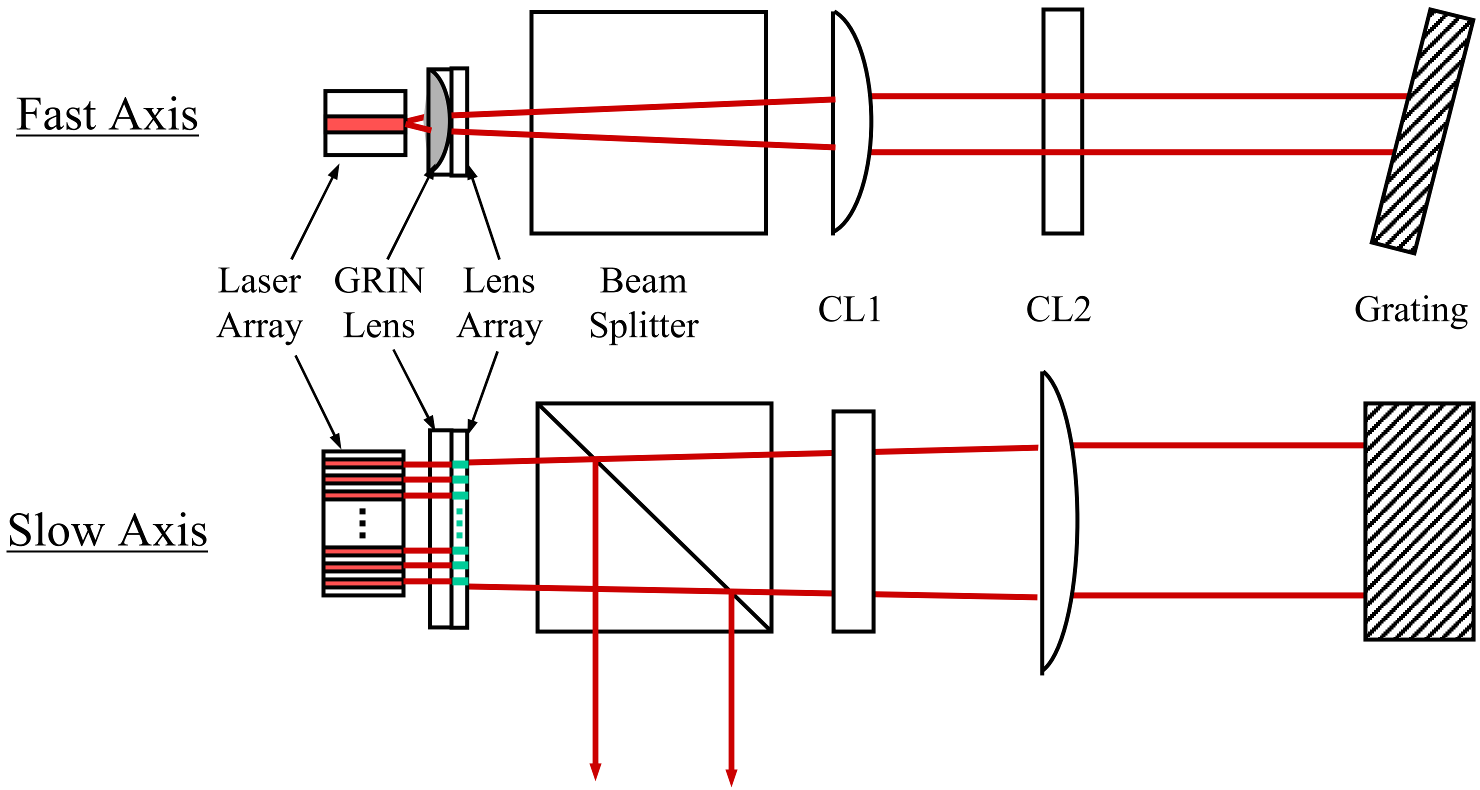
Spectra of Individual Broad-Area Laser Without Coupling and Spectrum of Total Output from Four Coupled Lasers



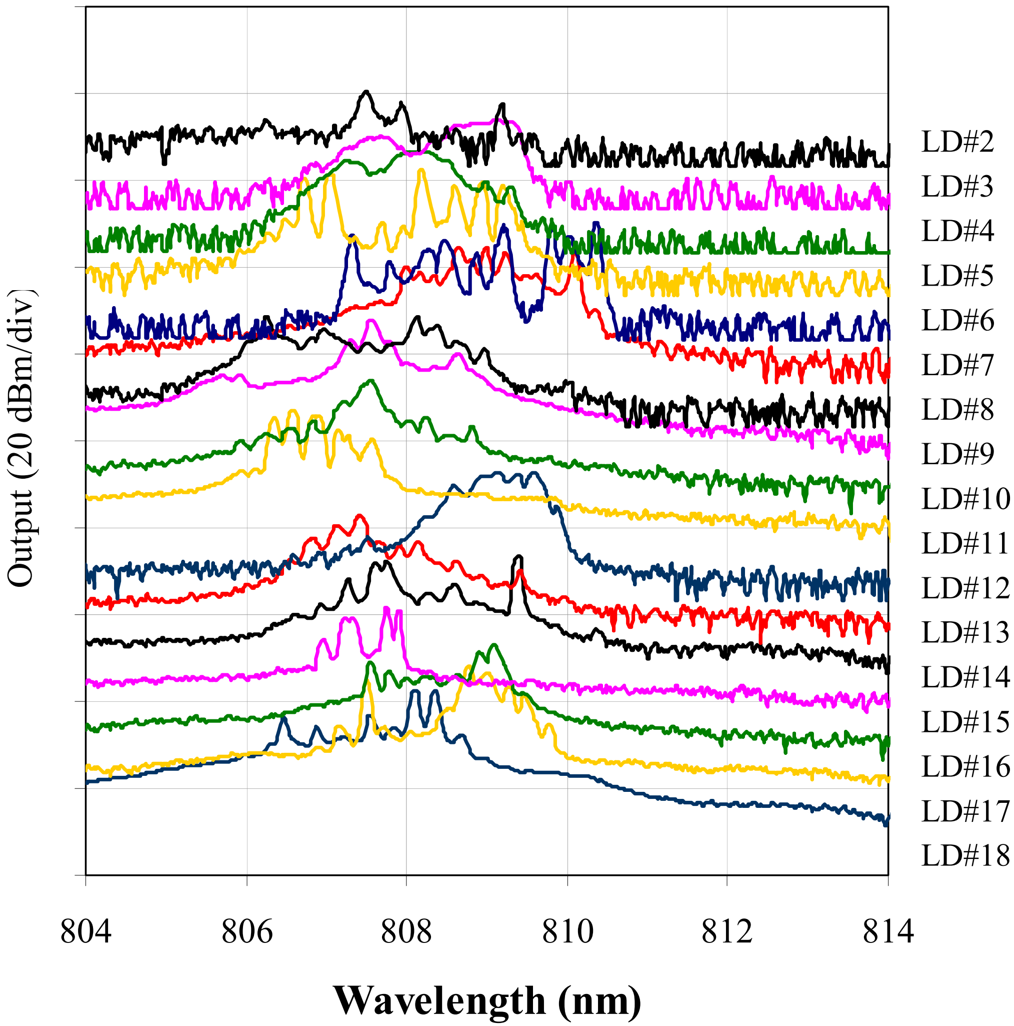
Experiment II

Self-injection Locking of Integrated Broad-Area Laser Array

Experimental Scheme

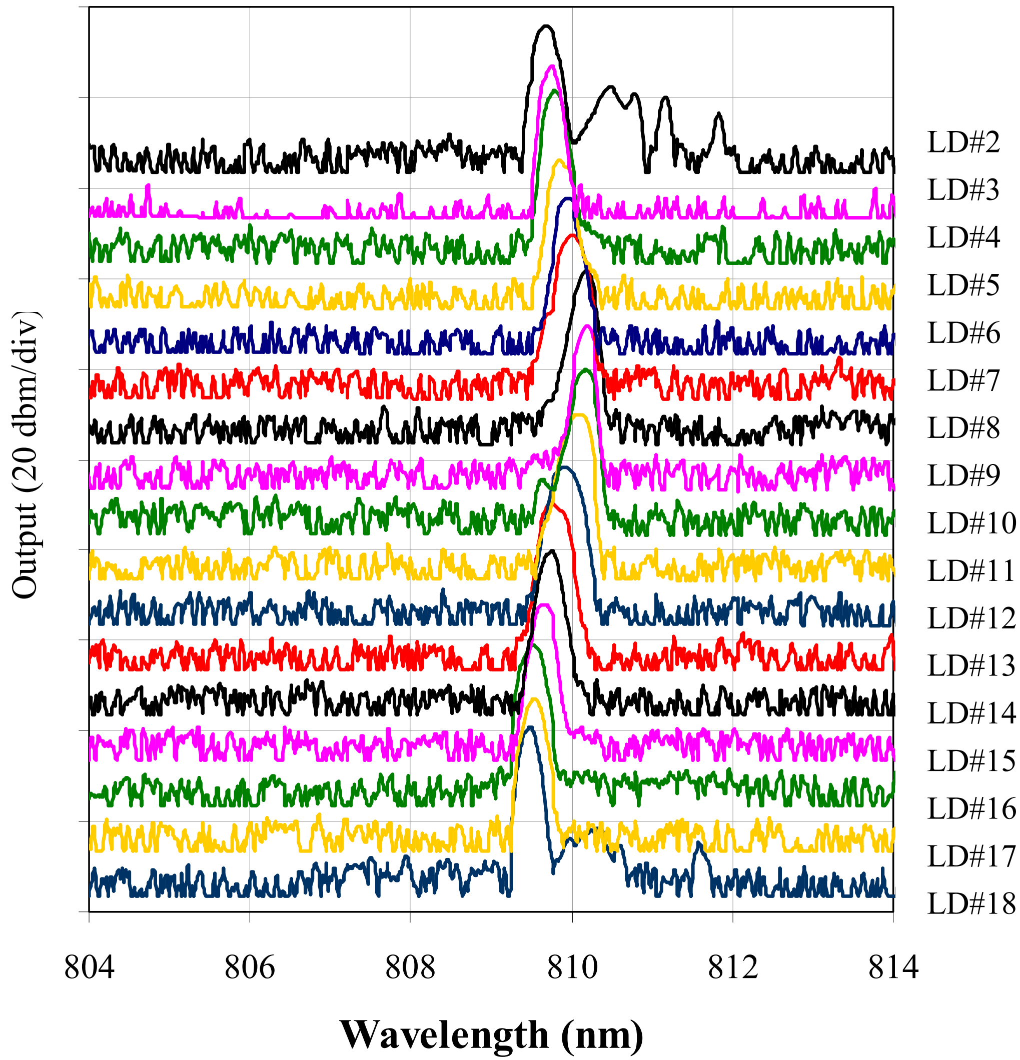


Optical Spectrum (Free-Running)



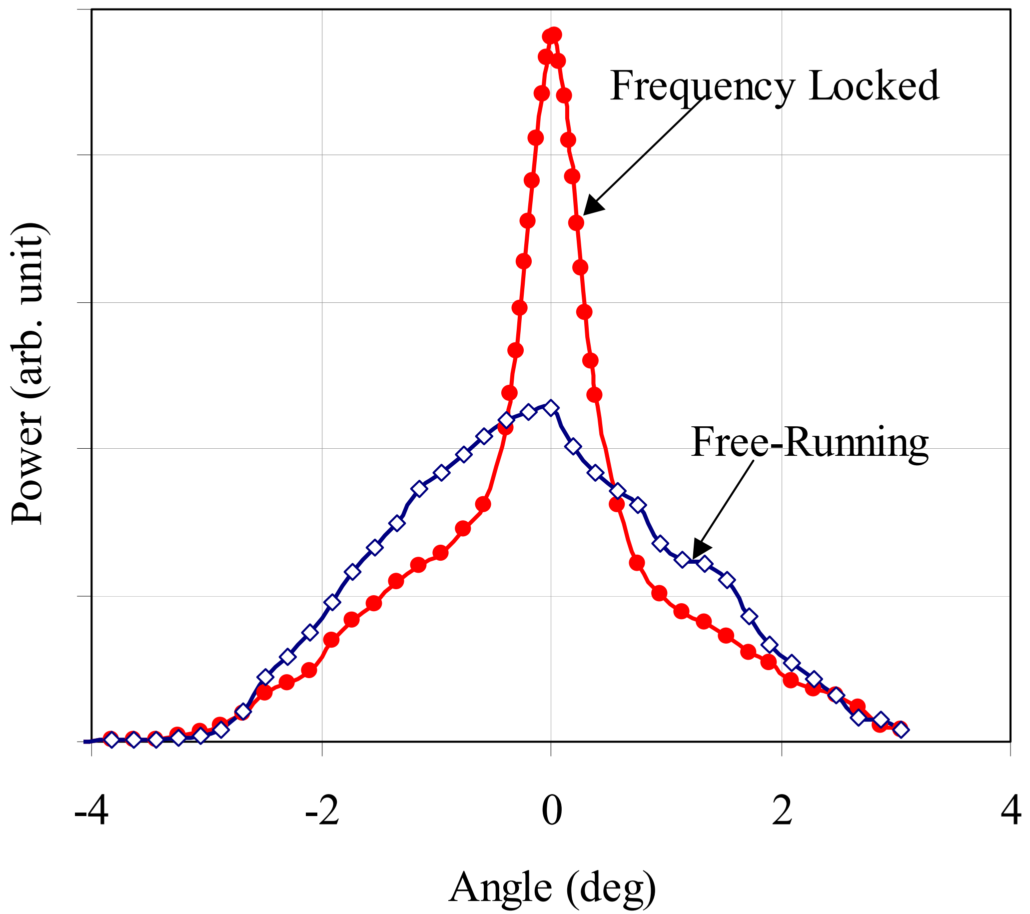
N = 19 Lasers in Array

Optical Spectrum (Frequency Locked)



N = 19 Lasers in Array

Far-Field Pattern of Broad Area Array (19 High Power Lasers)



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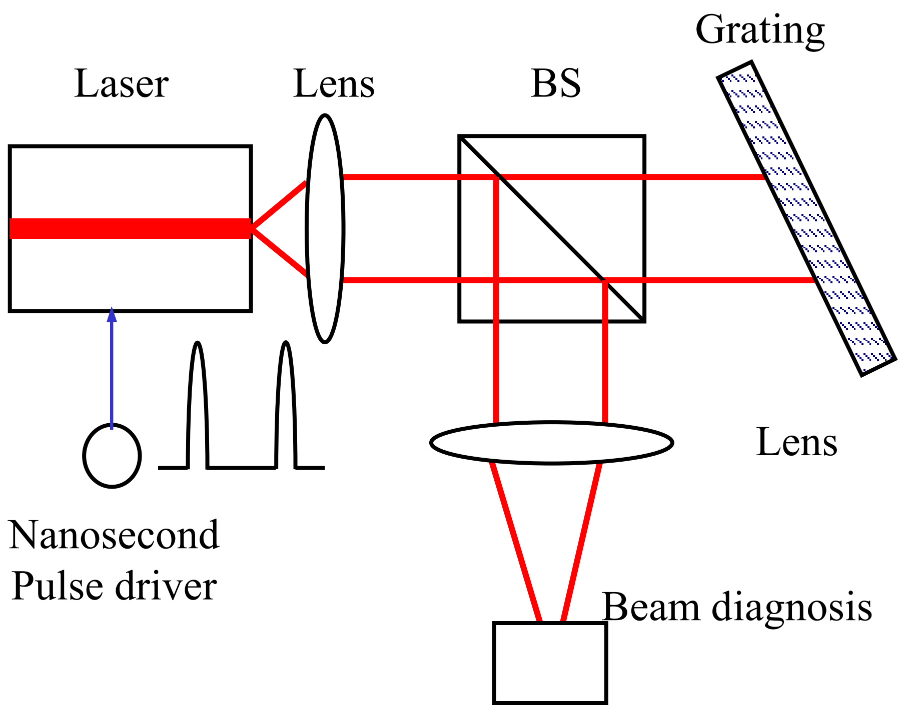
Experiment III

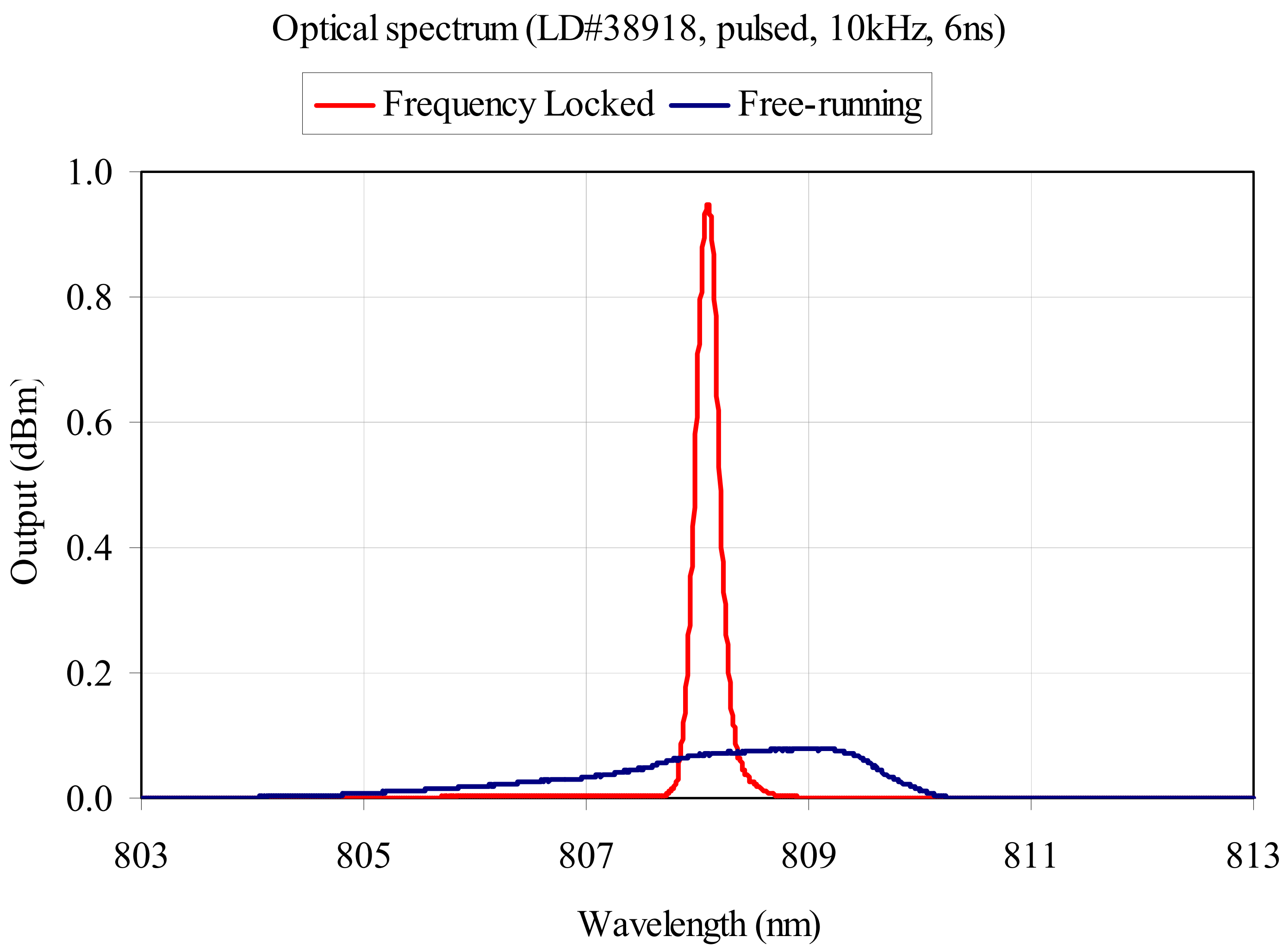
Self-injection Locking of Nanosecond Pulsed Broad-Area Laser

Nanosecond Broad-Area Laser Self-injection Locking

(Experimental Scheme)



Frequency-Locking of a Pulsed Laser



Phase Model of Two Coupled Lasers

$$\dot{\phi}_1 = \delta_1 + \kappa(\sin(\phi_1 - \phi_2)) - A_e \sin\phi_1$$

$$\dot{\phi}_2 = \delta_2 + \kappa(\sin(\phi_2 - \phi_1)) - A_e \sin\phi_2$$

Fixed Point Solutions

$$\delta_1 + \kappa(\sin(\phi_1 - \phi_2)) - A_e \sin\phi_1 = 0$$

$$\delta_2 + \kappa(\sin(\phi_2 - \phi_1)) - A_e \sin\phi_2 = 0$$

Injection Tuning

$$\delta_1 + \delta_2 \approx 0$$

Analysis of the Phase Model

$$\sin\phi_1 + \sin\phi_2 = 0$$

$$\delta_1 - \delta_2 + 2\kappa(\sin(\phi_2 - \phi_1)) - A_e(\sin\phi_2 - \sin\phi_1) = 0$$

The first equation implies that either (a) $\phi_2 - \phi_1 = (2m+1)\pi$, or (b) $\phi_2 + \phi_1 = 2m\pi$, where m is an integer. Solutions of class (a) imply: $\sin(\phi_2 - \phi_1) = 0$, yielding inconsistency.

Nonmonotonicity Transition Point

$$f(\phi) = -\delta - 2\kappa \sin\phi_c - A_c \sin\frac{\phi_c}{2} = 0$$

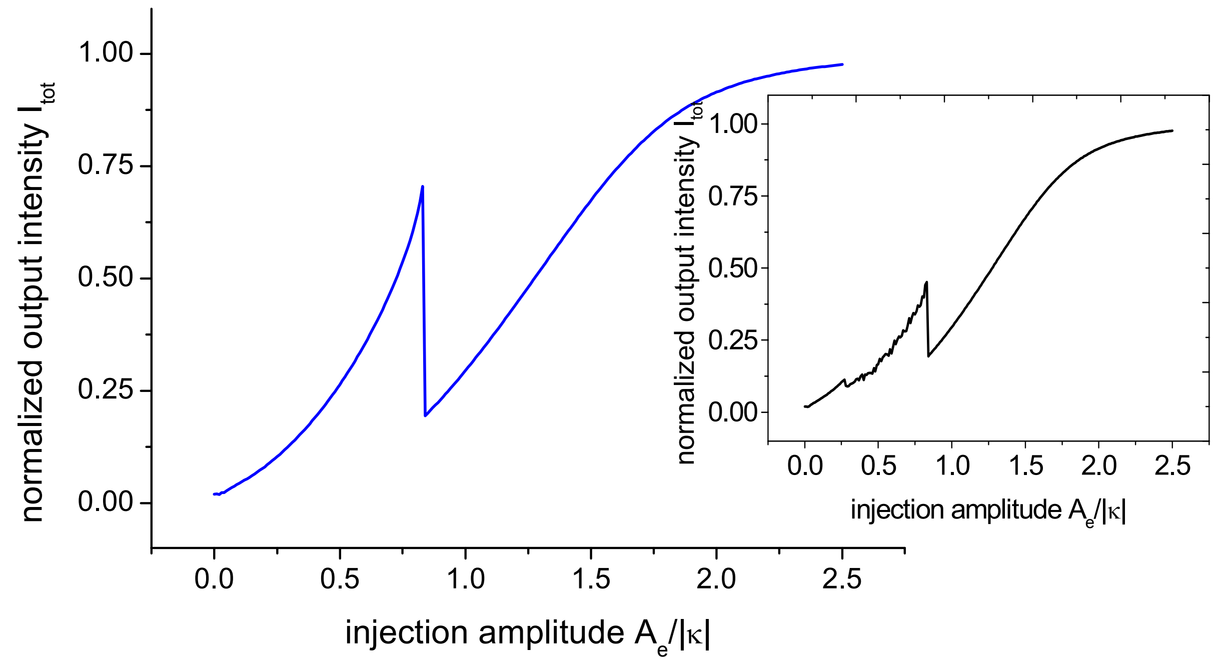
$$f'(\phi) = -2\kappa \cos\phi_c - A_c \cos\frac{\phi_c}{2} = 0$$

$$\tan\phi_c / 2 = z \qquad z^3 + (\delta / 4\kappa) z^2 + \delta / 4\kappa = 0$$

$$z = [-\frac{q}{2} + \sqrt{D}]^{1/3} + [-\frac{q}{2} - \sqrt{D}]^{1/3} - \frac{\delta}{12\kappa}$$

$$D = (p/3)^3 + (q/2)^2, \quad p = -\delta^2 / 48\kappa^2 \quad \text{and} \quad q = (\delta / 4\kappa) + (\delta^3 / 864\kappa^3)$$

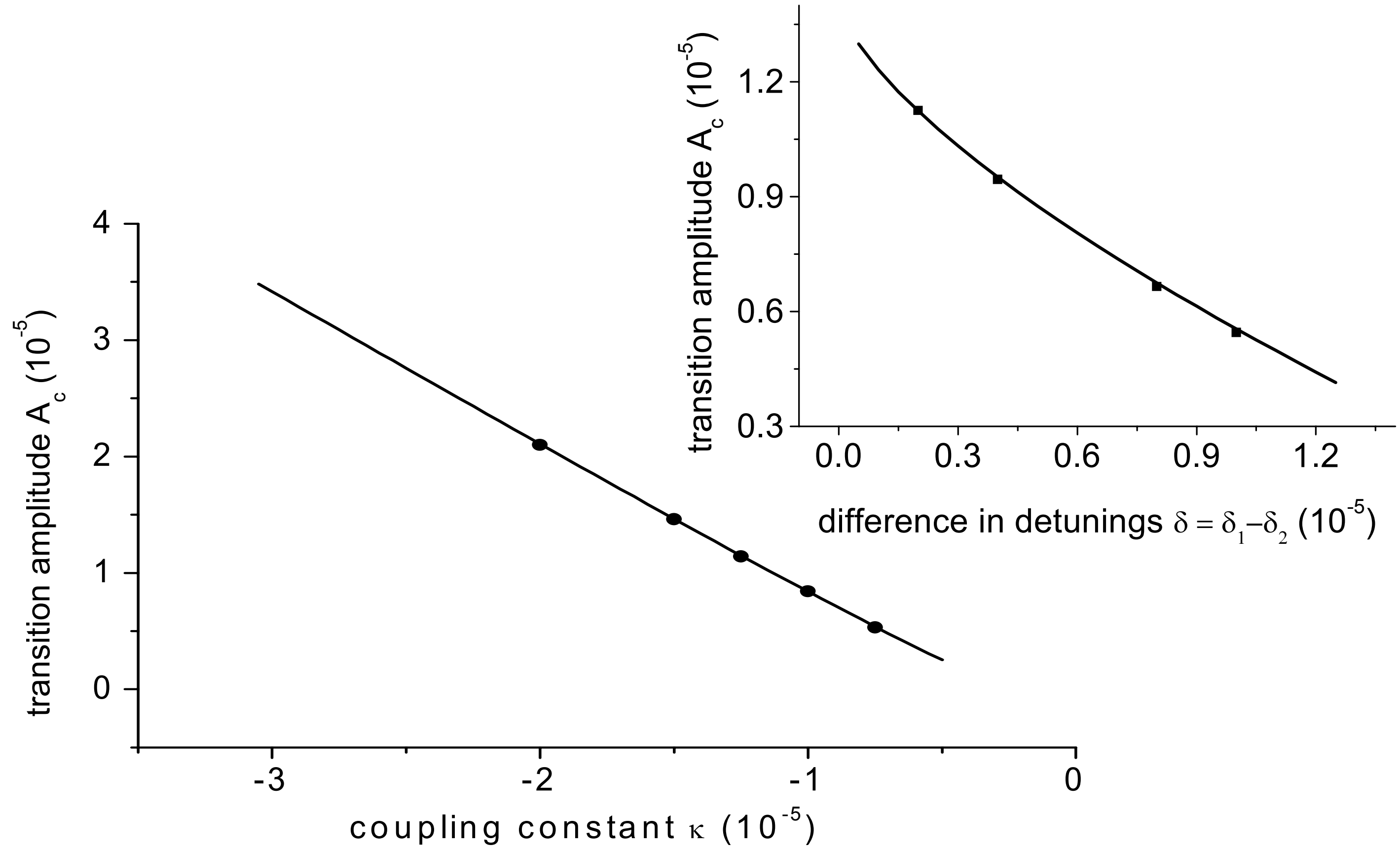
Nonmonotonicity



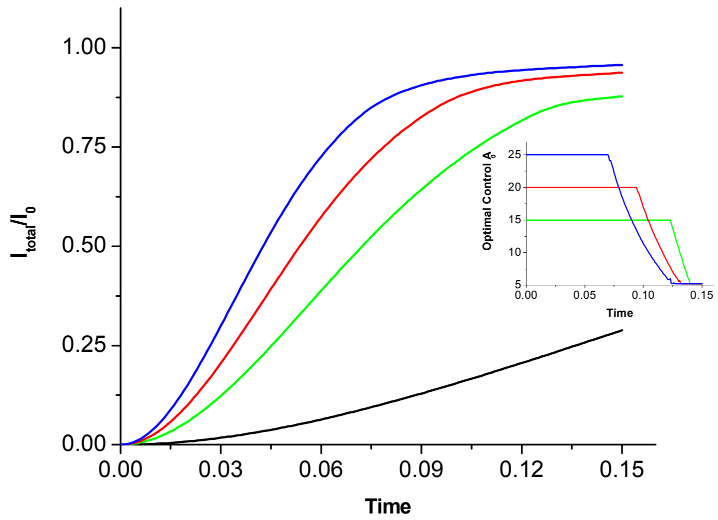
$$A_c = -2\kappa \frac{1 - z^2}{\sqrt{1 + z^2}}.$$

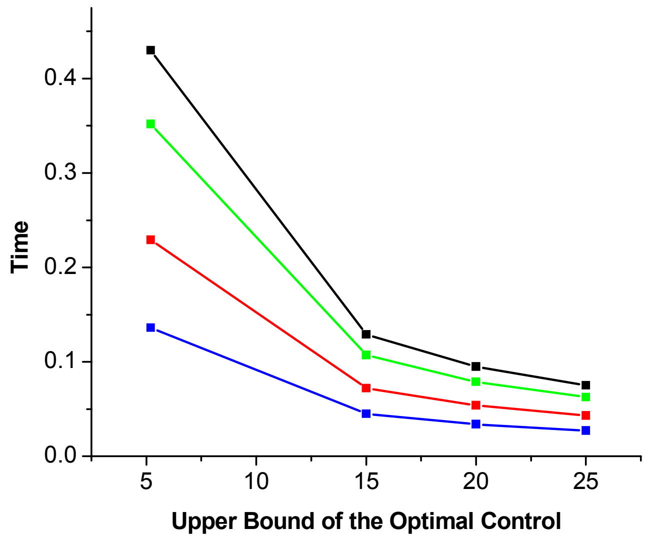
A. I. Khibnik, Y. Braiman, V. Protopopescu, T. A. B. Kennedy, and K. Wiesenfeld, Phys. Rev. A 62, 063815 (2000).

Comparison of the Analysis with Numerical Simulations



Optimal Control of the Transient Behavior





Summary

- **Synchronization and coherent beam coupling of high-power laser array (19 lasers) - high coherence, better directionality, high intensity.**
- **Experimental setup of synchronizing high-power broad-area semiconductor lasers via injection locking**
  - **Conditions for injection locking of broad-area lasers.**
  - **Simultaneous injection of two broad-area lasers in a 19-laser array.**
- **Experimental investigations and results**
  - **Temporal dynamics of the injection-locked laser**
  - **Amplification of the injection light**
  - **Phase coherence between injection-locked lasers.**

Challenges

Array inhomogeneity

Limited injection power

Future work

Separate control of individual laser

Cascaded injection scheme