ECC8 June 17, 2004

Dynamics and Synchronization of Broad-Area Semiconductor Laser Arrays

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This research was supported by the U.S. Department of Energy, Office of Basic Energy Sciences, and by the Office of Naval Research.
The Oak Ridge National Laboratory is managed for the U.S. DOE by UT-Battelle, LLC, under contract No. DE-AC05-00OR22725.

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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

$$E_j(t) = E_j \exp(-i\omega_j t) + cc$$

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

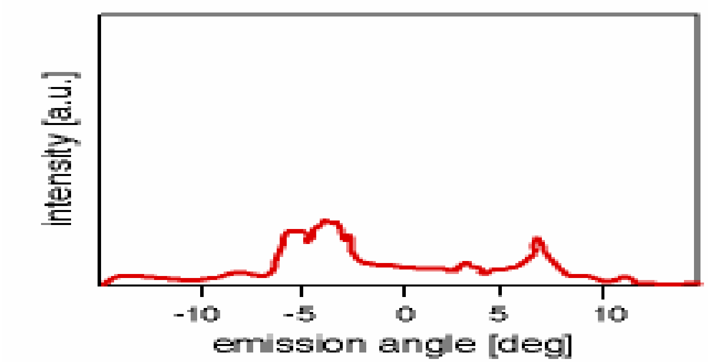
E_j - complex amplitude

ω_j - the frequency

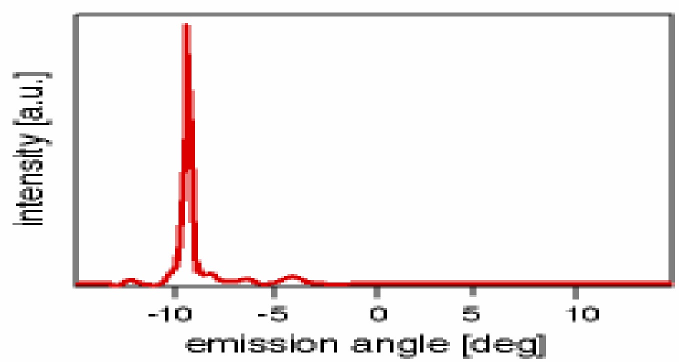
$$E_j = \sqrt{I_j} e^{i\phi j}$$

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

$\Rightarrow I \sim N^2 I_0$

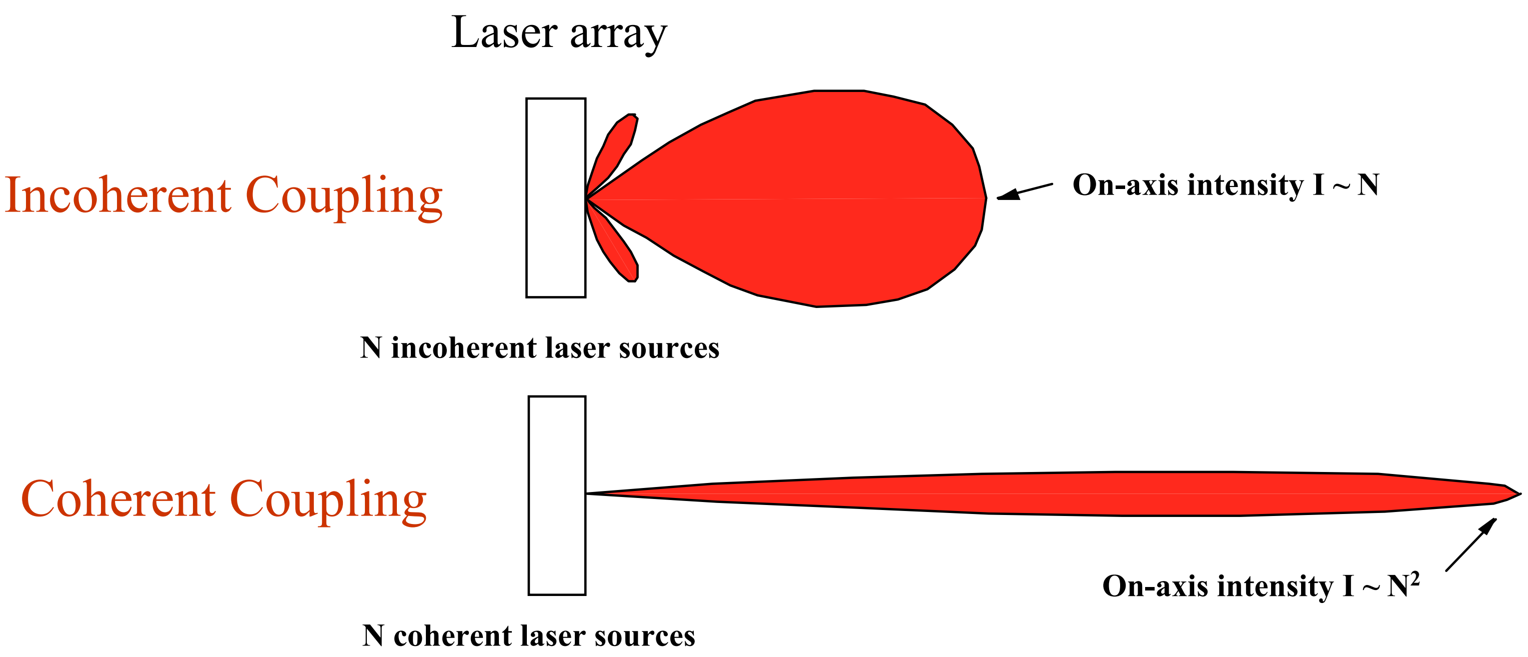


Noncoherent addition



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

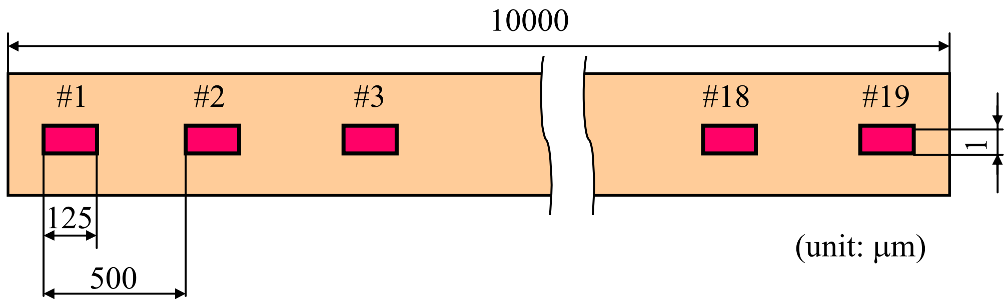
Conditions for coherent beam coupling

- –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

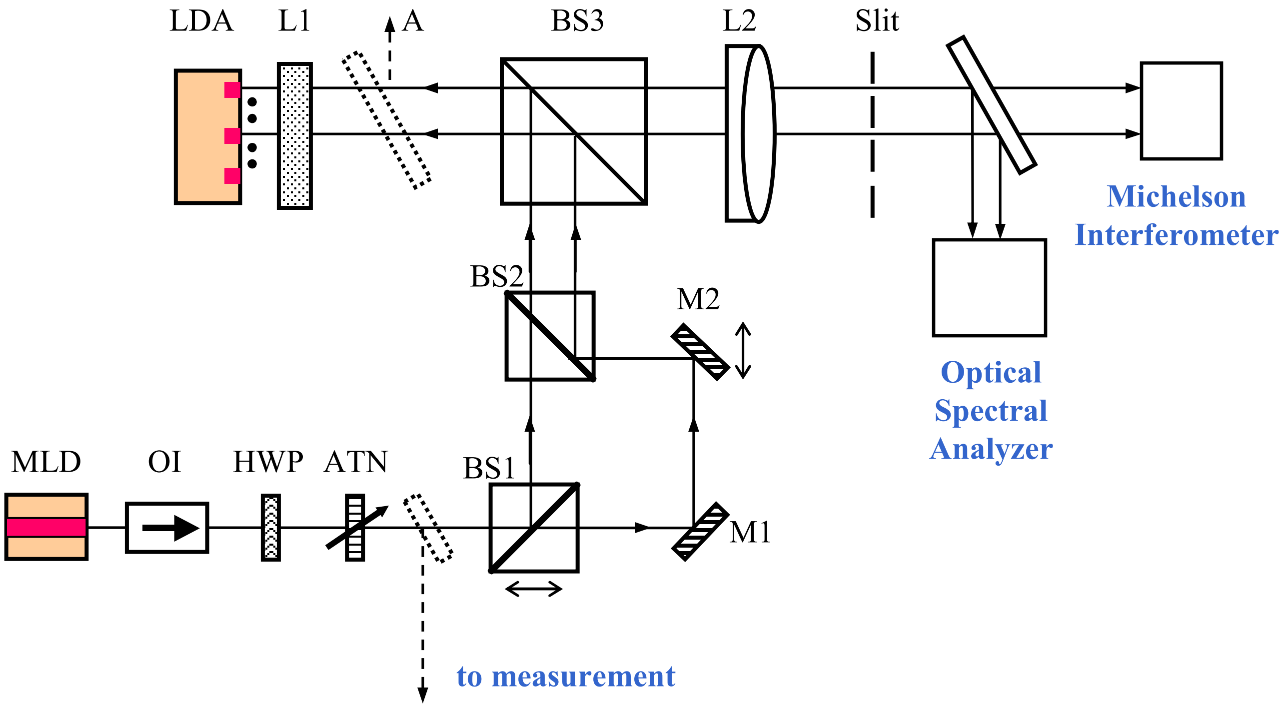
Single Broad-Area Laser Diode — aperture < 100 μm ×1 μm, power: < 1 W

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

Our Objective

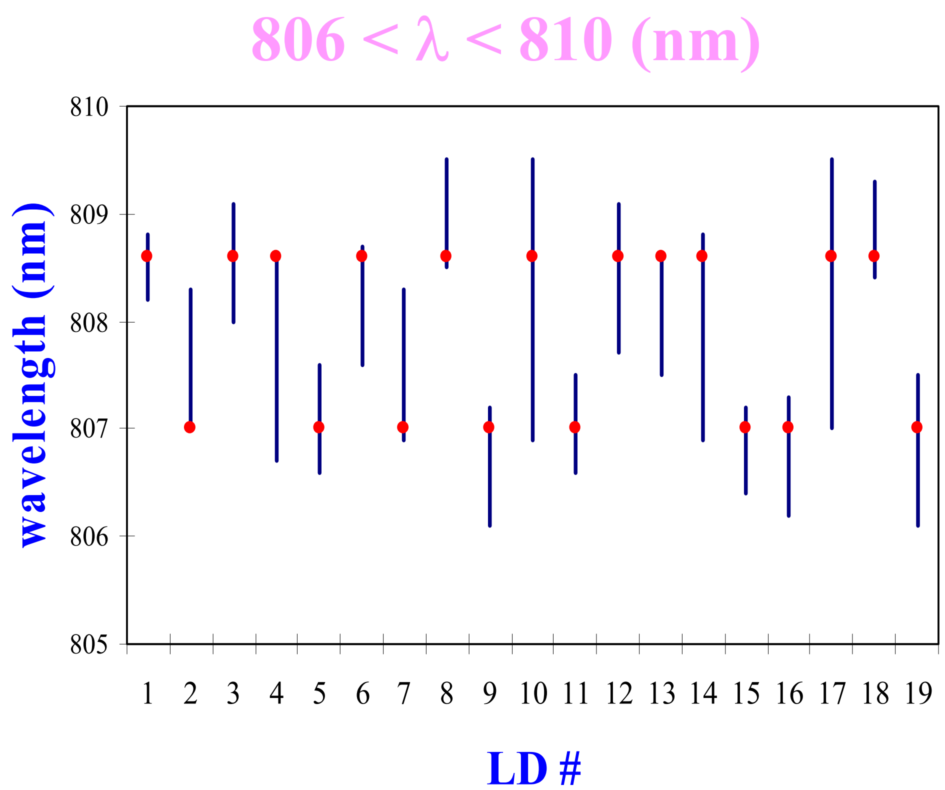
Synchronization and coherent coupling of a broad-area laser array

Experimental Setup of Injection Locking



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

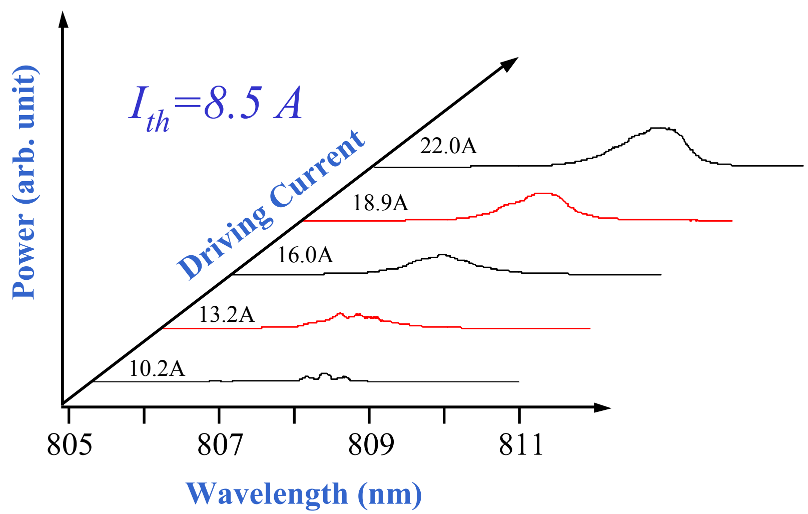
Wavelength Span of all 19 Lasers



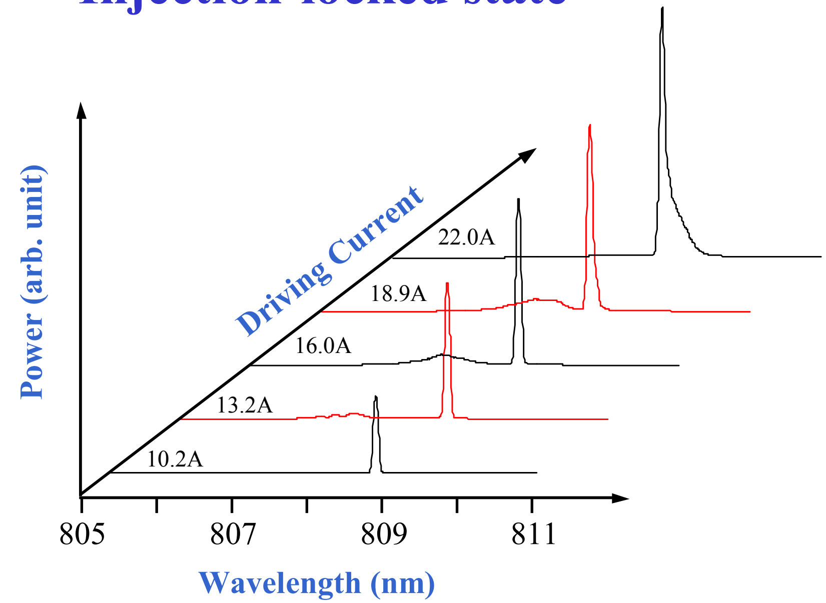
● : injection locking frequency around the driving current I_d~1.5 I_{th}

Frequency Matching for Injection Locking

Free-running state



Injection-locked state

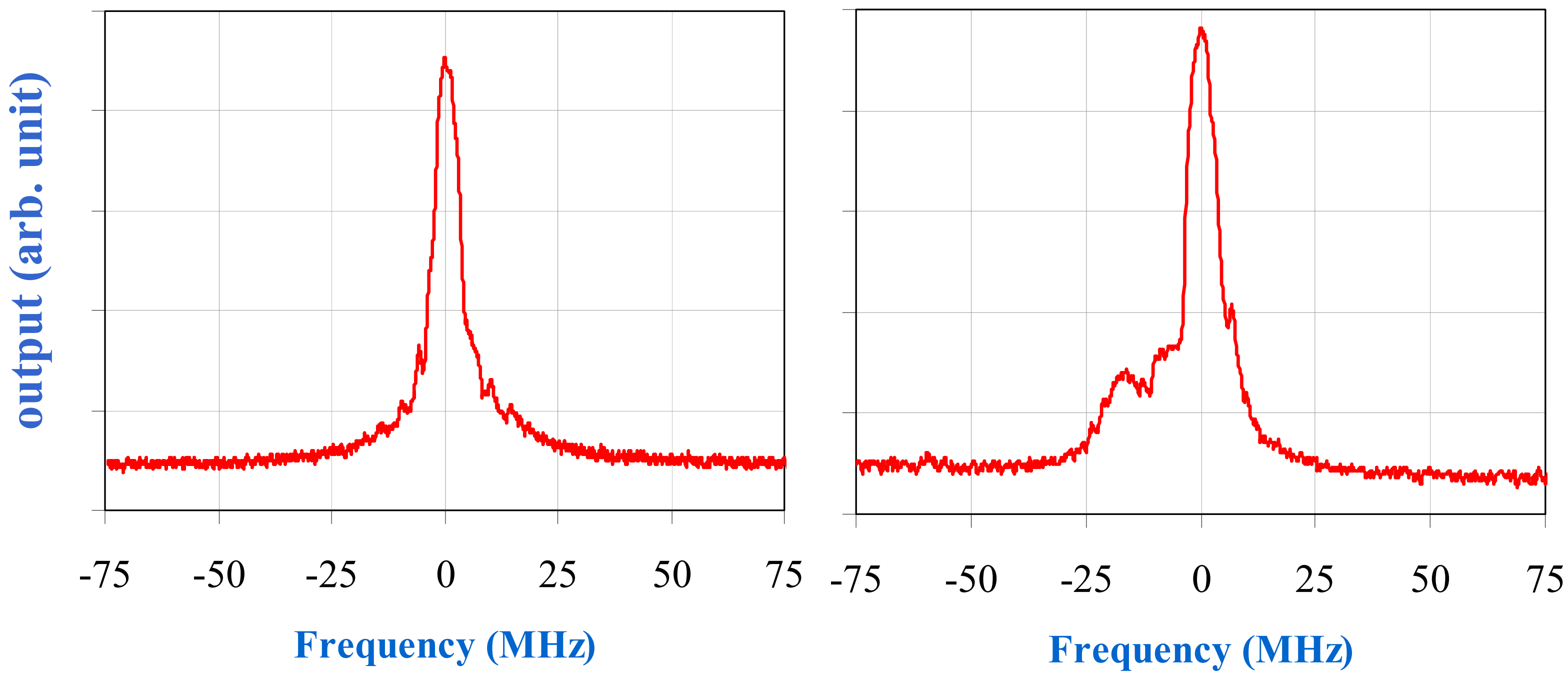


Condition for Injection Locking

- **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

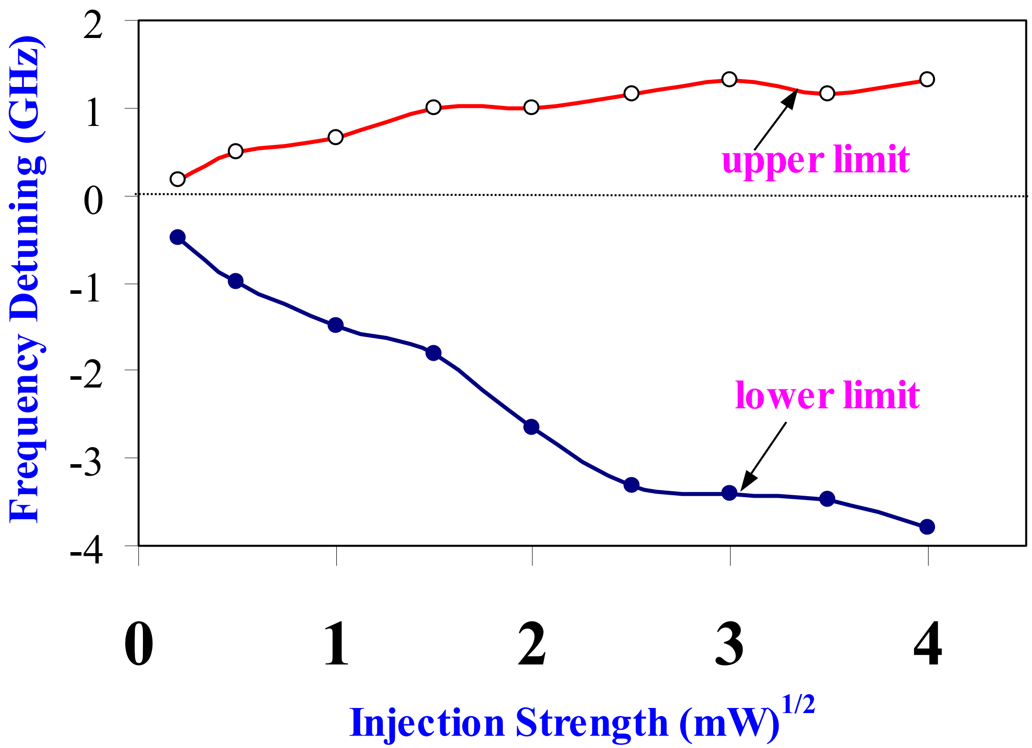


I_d=11.2A

I_d=22.0 A

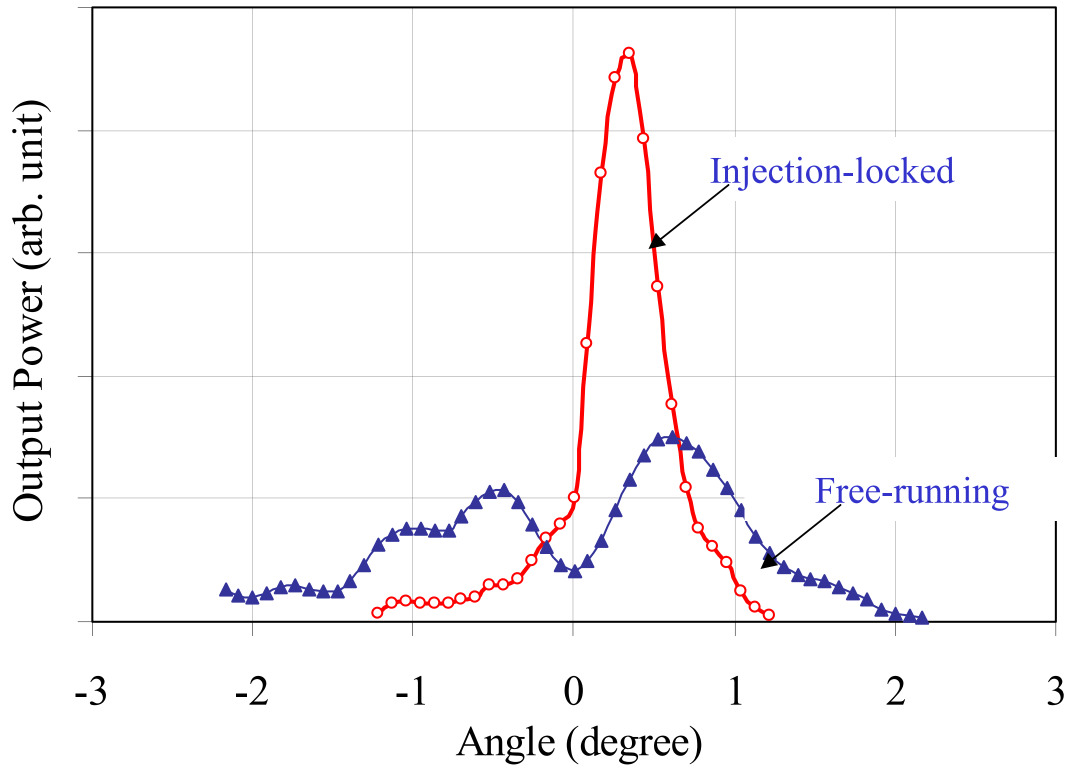
Spectrum Bandwidth of the Order of 10 MHz

Injection Locking Range



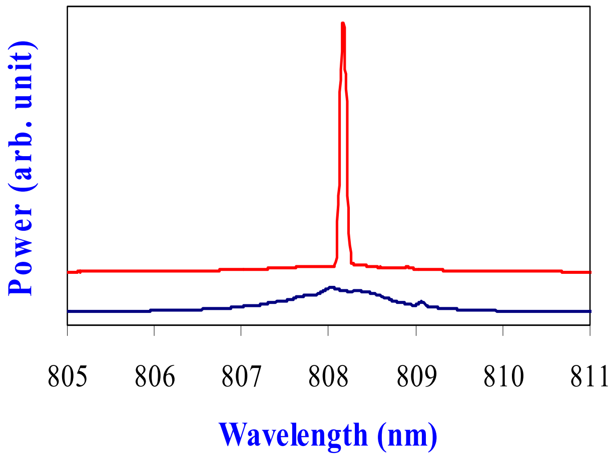
- Stable Locking Range
- At Low Drive Current, the Frequency Range for Stable Locking is Linear with the Injection Strength

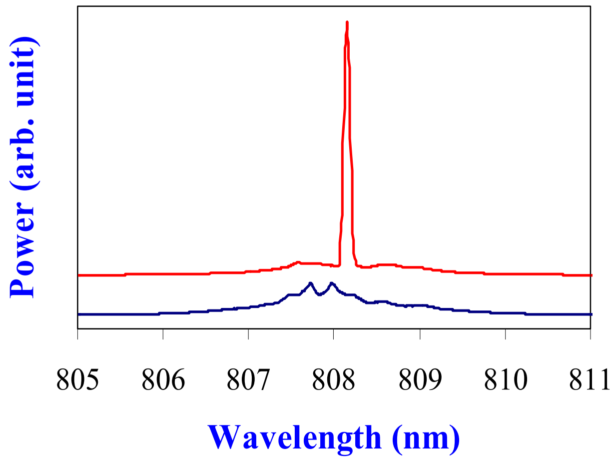
Far-Field Pattern at Injection-Locking



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

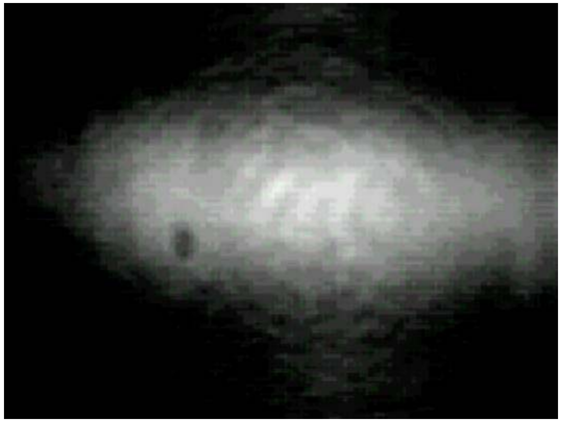




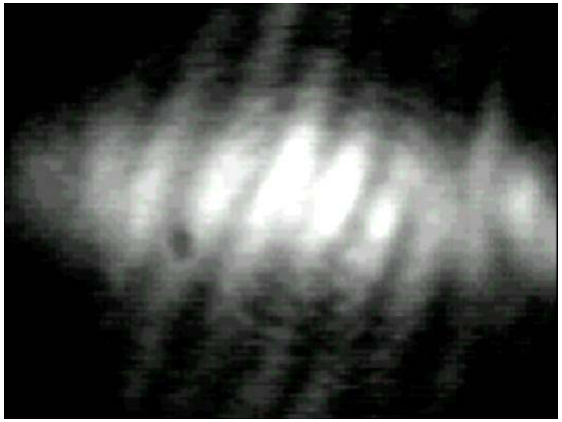
LD#7 **LD#12**

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

Interference Between Injection-Locked Lasers



Before Injection Locking

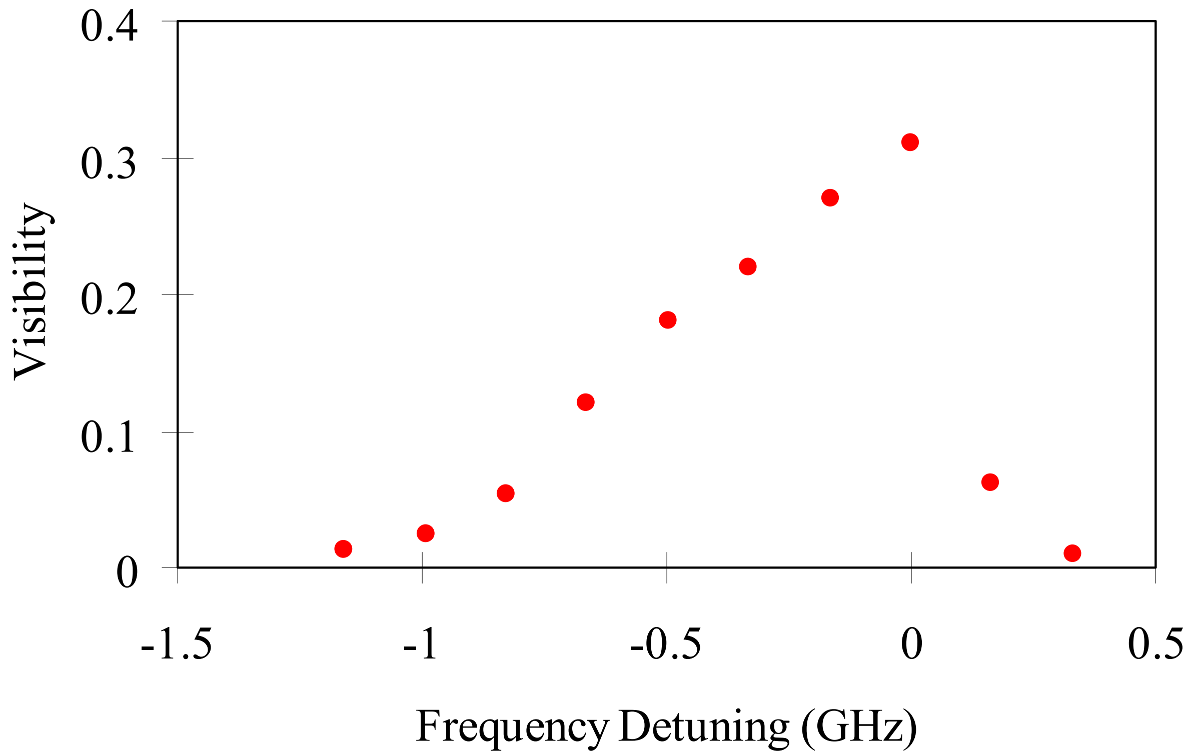


After Injection Locking

Stable Phase Relationship Between Lasers
Locking of Spatial Modes

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

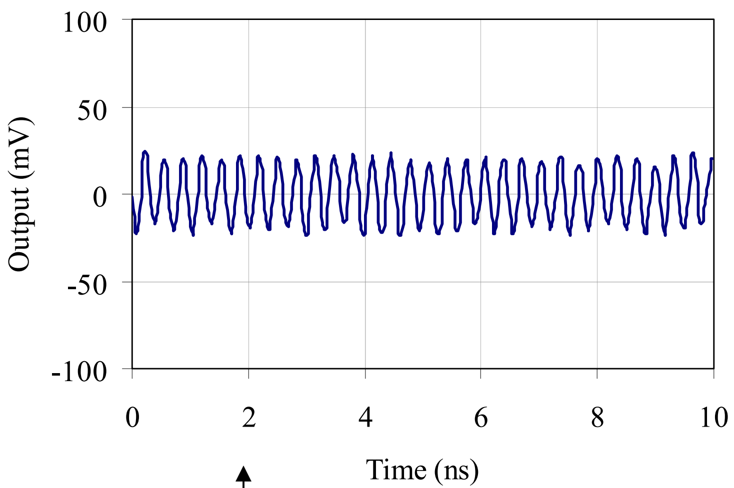
Parameter Dependence



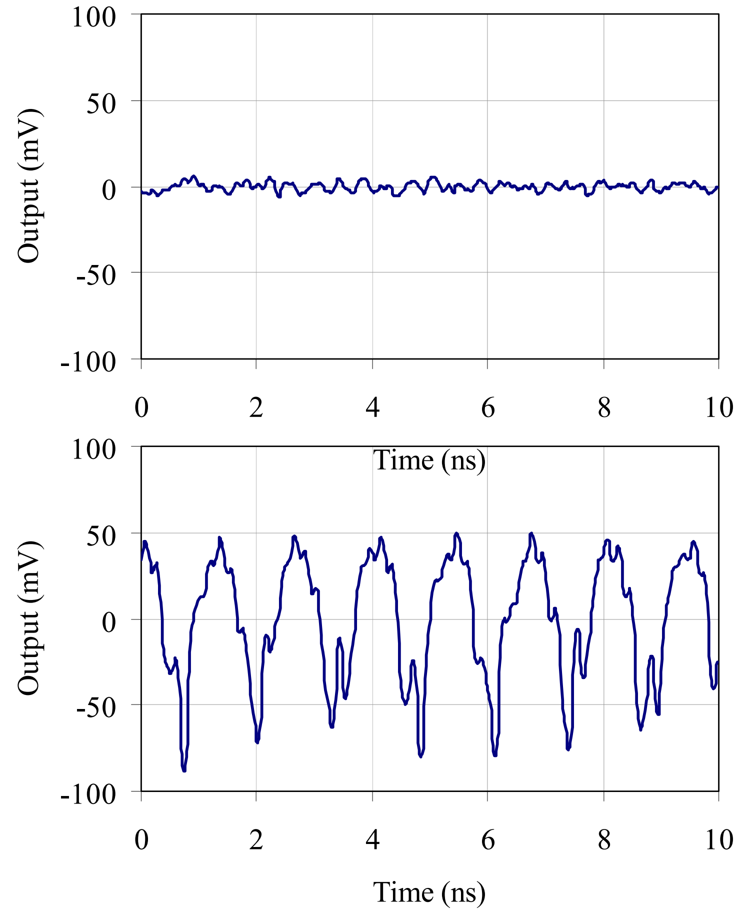
Sensitive dependence of simultaneous injection locking on frequency matching

Temporal Dynamics

Free-running state



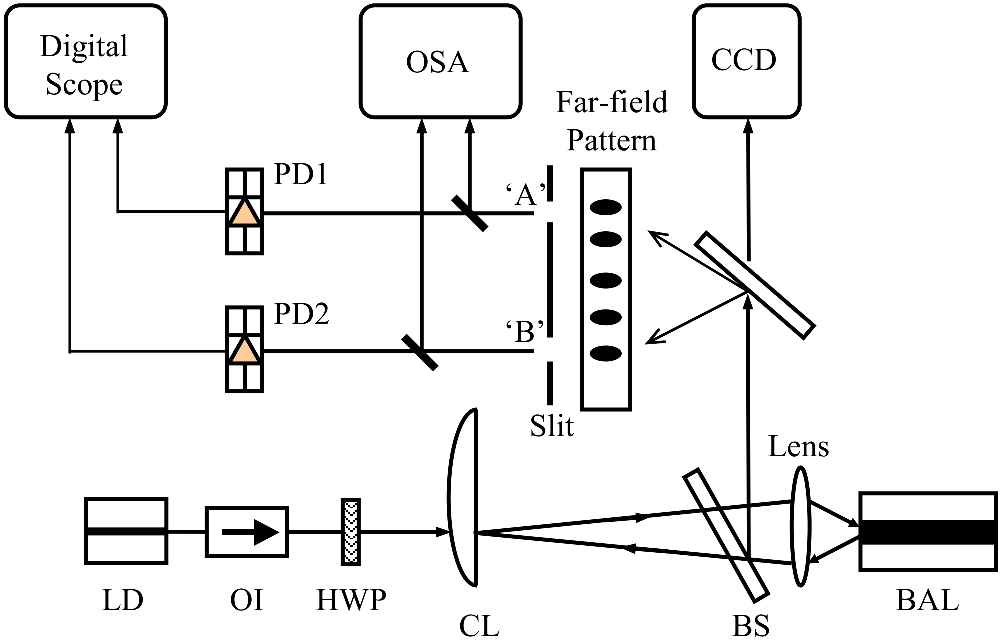
Injection-locked states



Relaxation oscillations (~3GHz)

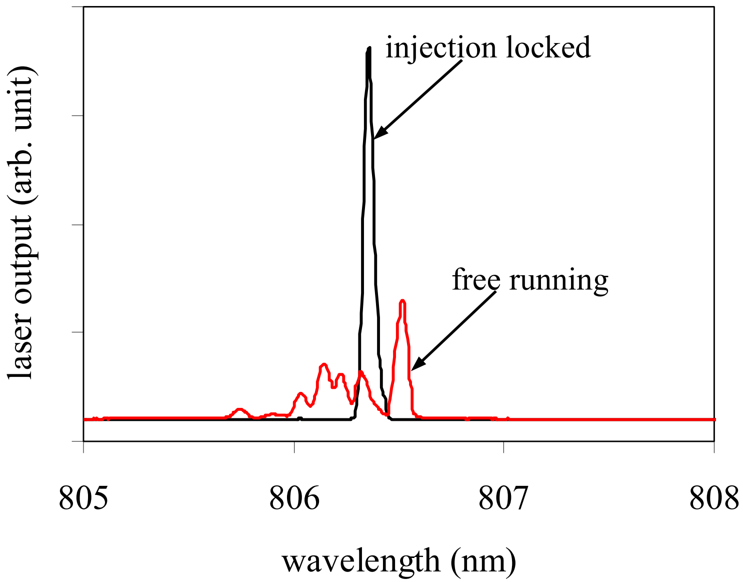
Bistability between stabilized state and low-frequency (~700 MHz) oscillation state

Spatial-Temporal Dynamics

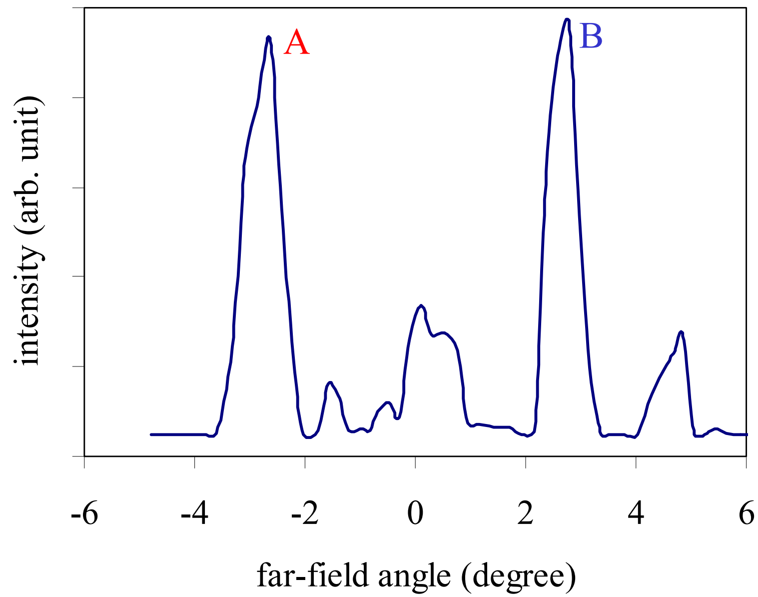


Experimental Setup of Measuring Temporal Waveform of Different Spatial Modes

Optical Spectrum

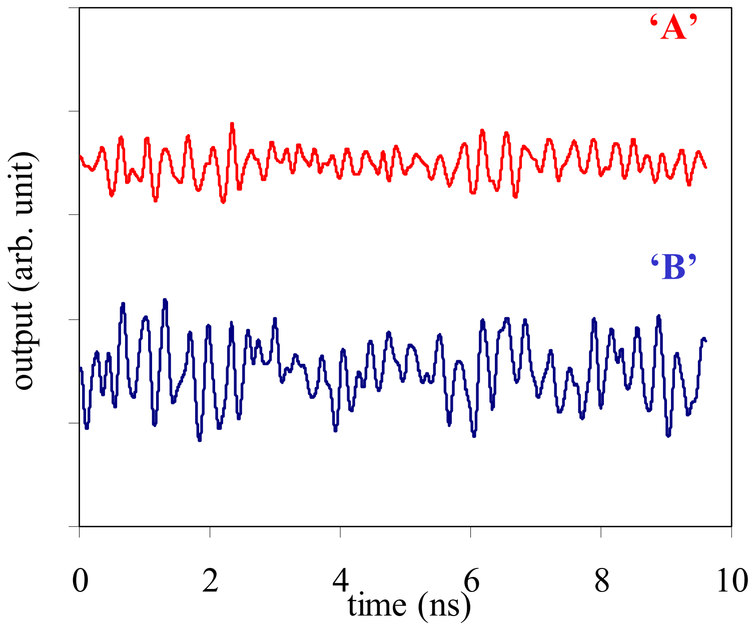


Far-Field Pattern

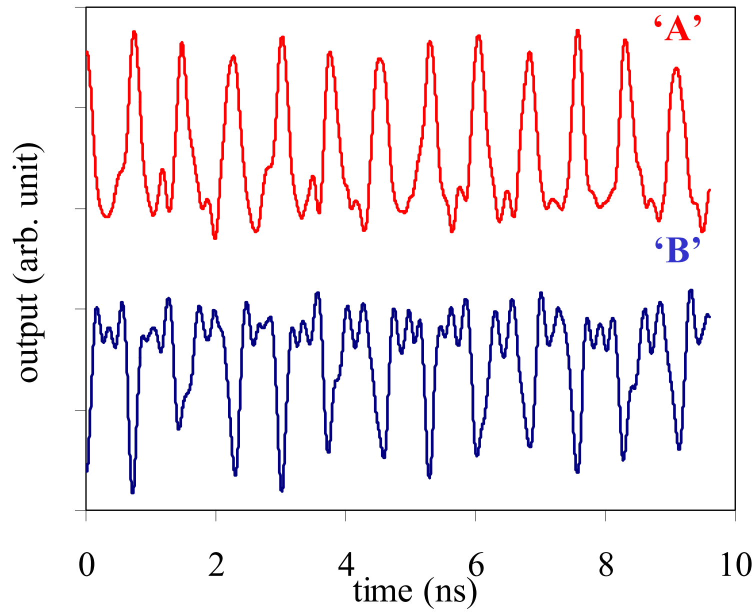


Temporal Dynamics of Different Spatial Modes

Free-Running

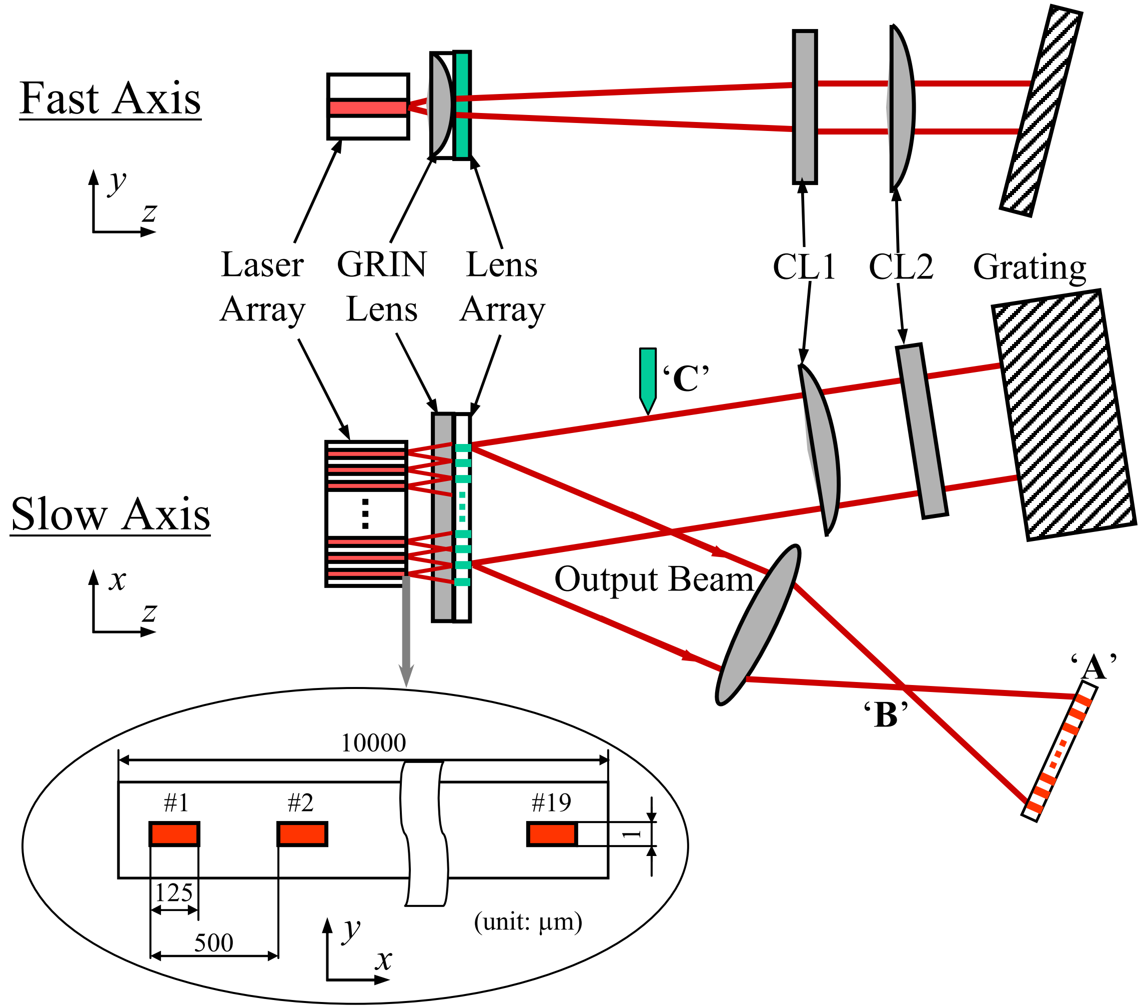


Injection Locked



Self-injection Locking of Coupled Individual Broad-Area Lasers

Experimental Scheme



Our Experimental Design

•Since the broad-area laser emitter has a very asymmetric emission aperture (125 μm×1 μm), the laser output shows different beam qualities along fast and slow axes.

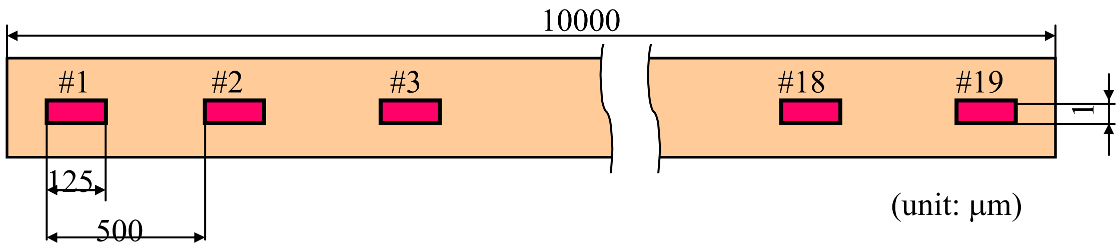
•Along the fast axis direction, the emission size (~ 1 μm) is close to the laser wavelength (around 0.8 μm) and the output beam shows a fundamental Gaussian mode with a large divergence angle.

•The beam collimation along the fast axis is conducted by a gradient index (GRIN) cylindrical lens with a very short focal length (1.3 mm) and large numerical aperture (0.5).

•Along the slow axis direction, the emission size (125 μm) is much larger than the laser wavelength and the output beam exhibits higher order modes with multiple lobes in the far-field pattern.

•A cylindrical lenslet array to collimate the array output in the slow-axis direction. The separation between each lens is designed to match the laser array.

High Power Laser Array



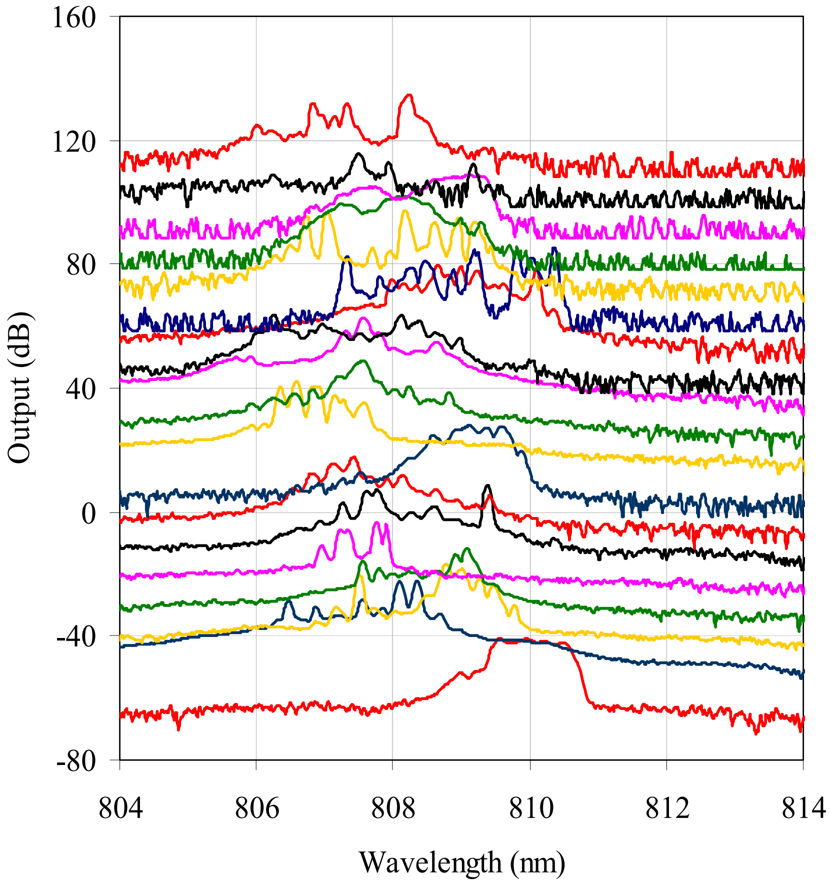


Figure 1a. Spectrum of all 19 emitters in a free running mode.

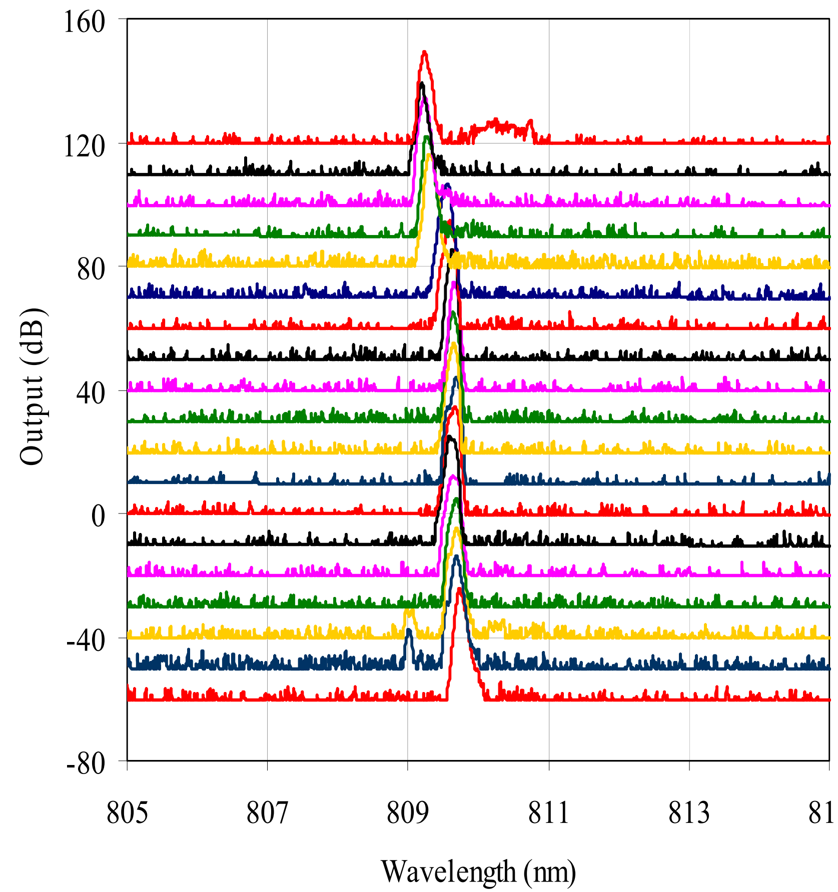


Figure 1b. Spectrum of all 19 emitters in the synchronized mode.

Accomplishments:

- Demonstrated single mode emission from high power laser array
- Demonstrated wavelength tunability over the range of 10 nm

Future work: achieve synchronization of stack arrays to coherently combine power from large laser arrays

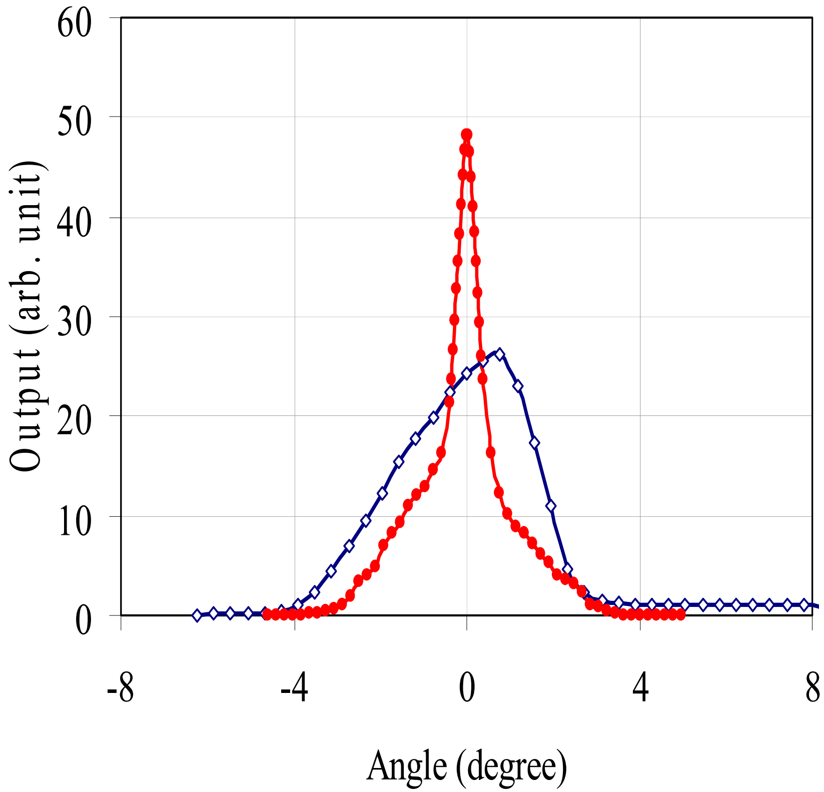


Figure 2. Far-field pattern from the free running (blue line) and the synchronized (red line) array.

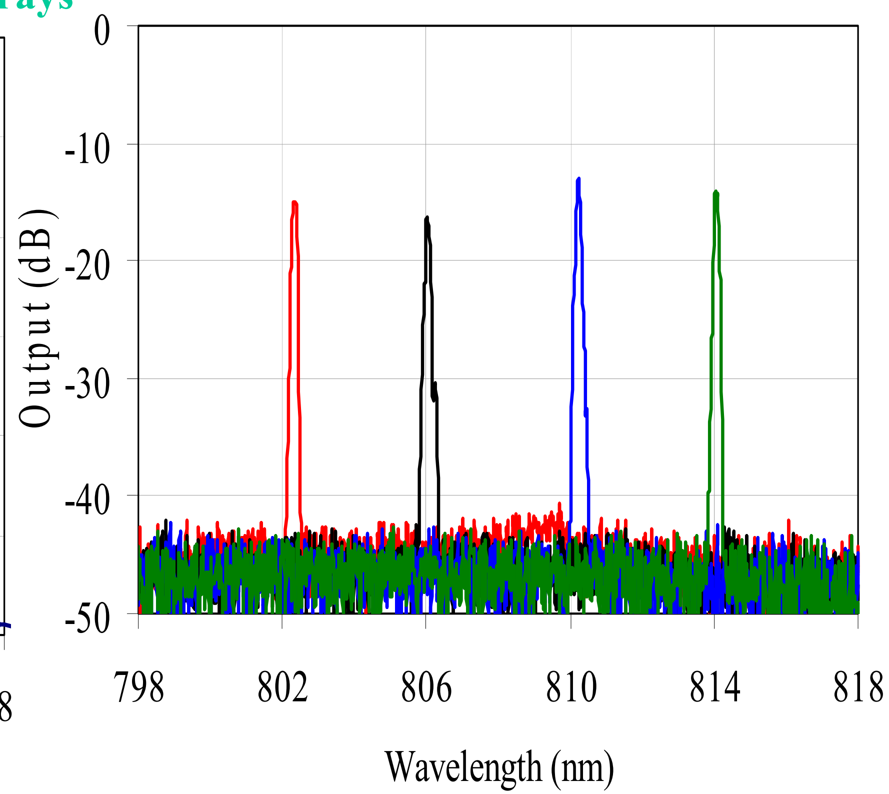
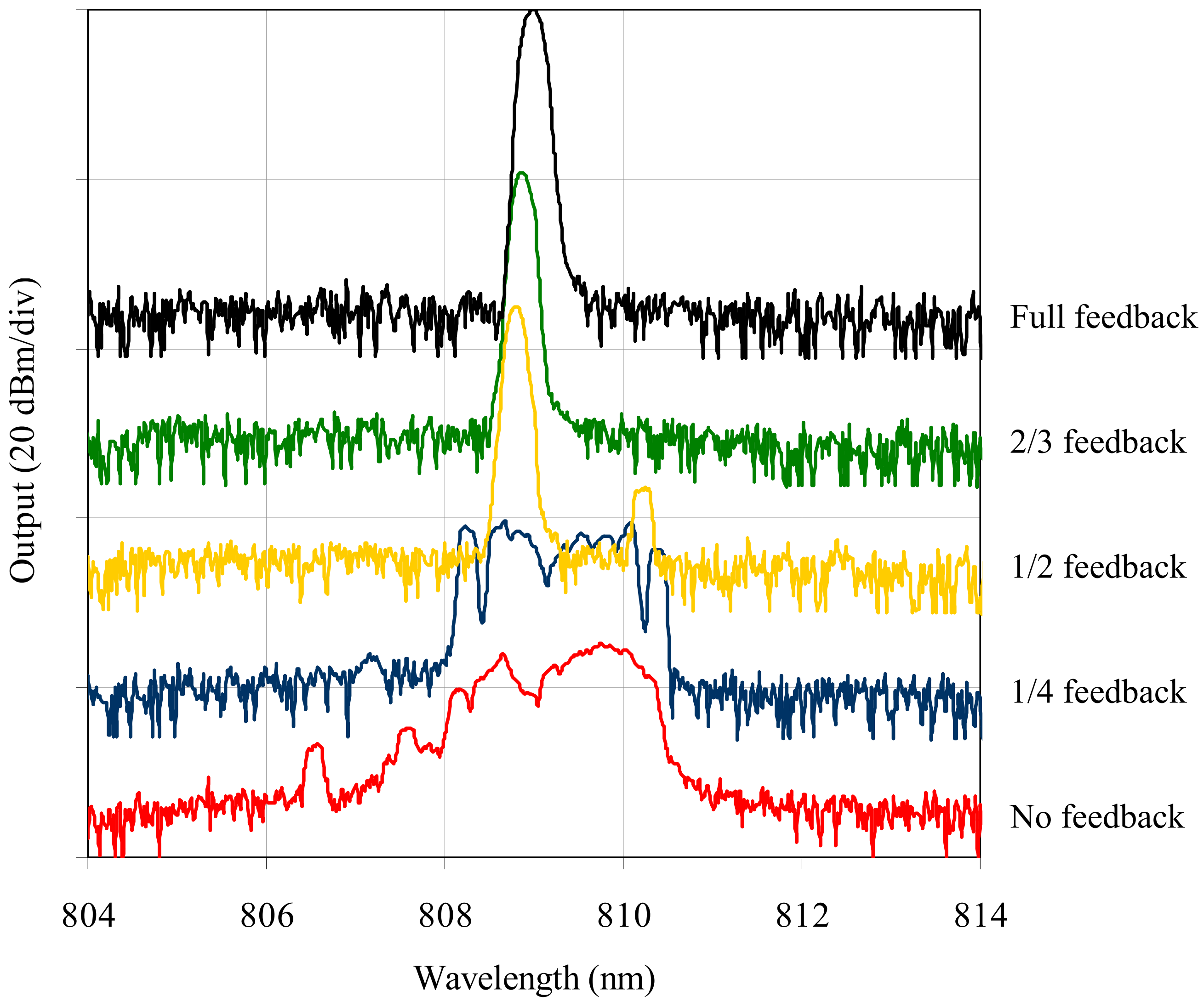


Figure 3. Power spectrum of laser array showing tunable wavelengths over 10nm range.

Effects of Feedback on Specific Laser

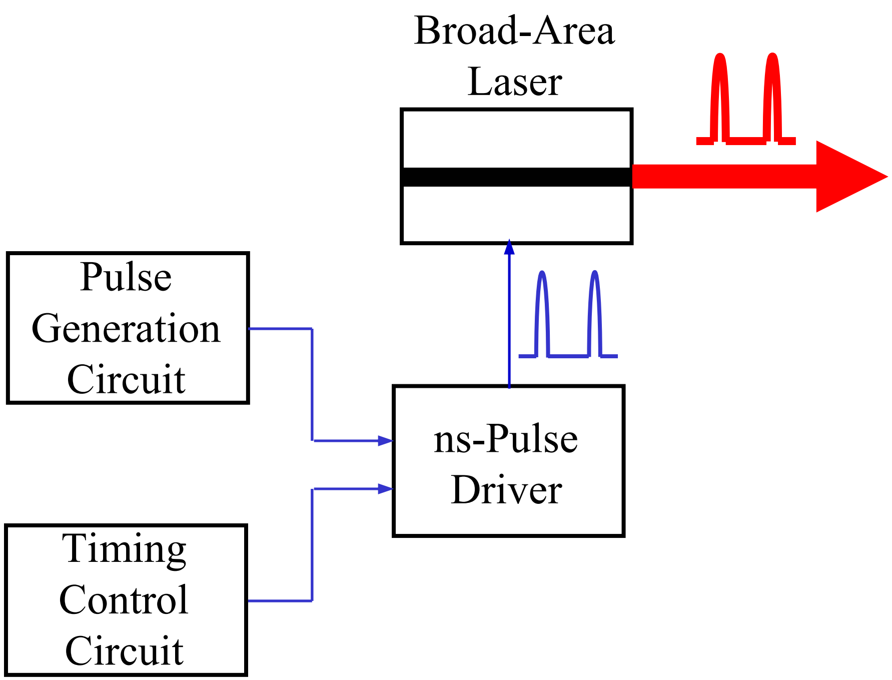


Self-injection Locking of Nanosecond Pulsed Broad-Area Laser

Outline

- **Nanosecond pulse generation in broad-area lasers**
- **Frequency locking of lasers with external cavity**
- **Synchronization of pulsed broad-area lasers**

Nanosecond Pulse Generation in Broad-Area Lasers



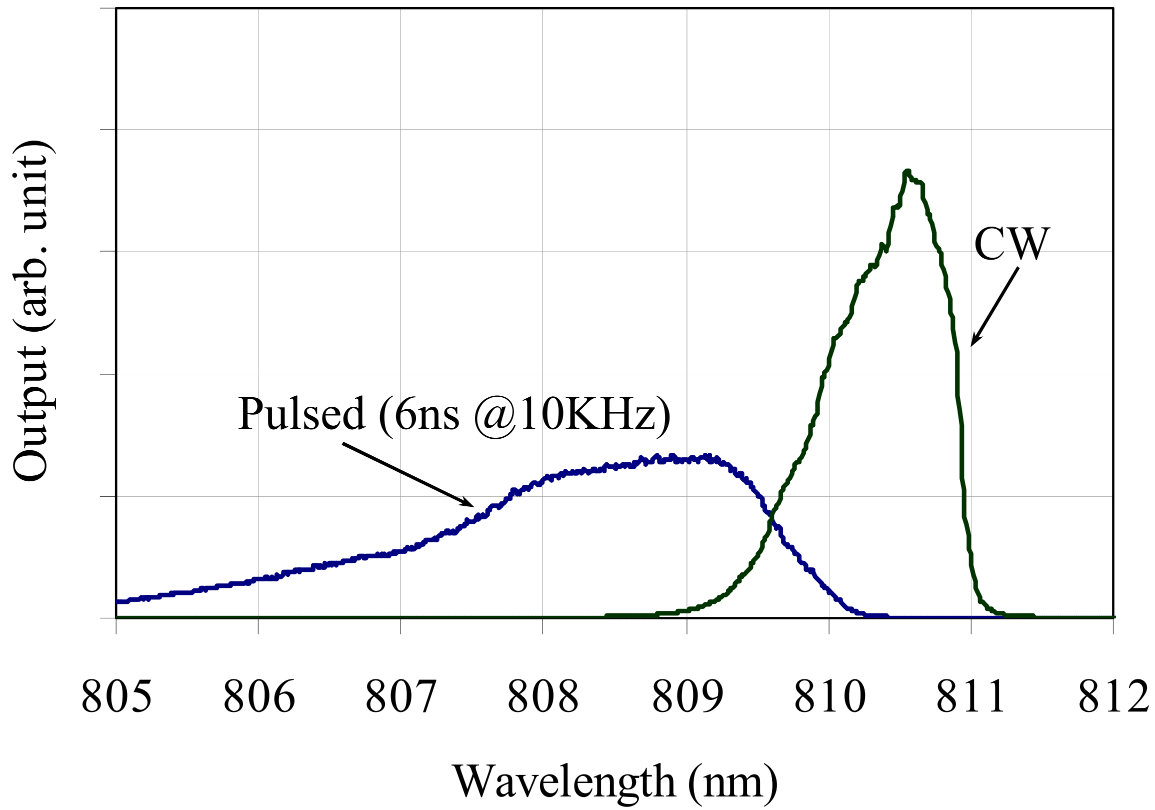
<u>Adjustable pulse amplitude, pulse duration, and repetition rate</u>

Pulse amplitude: 0~40 A (40 W)

Pulse duration: 5~1000 ns

Repetition rate: 4 KHz~1 MHz

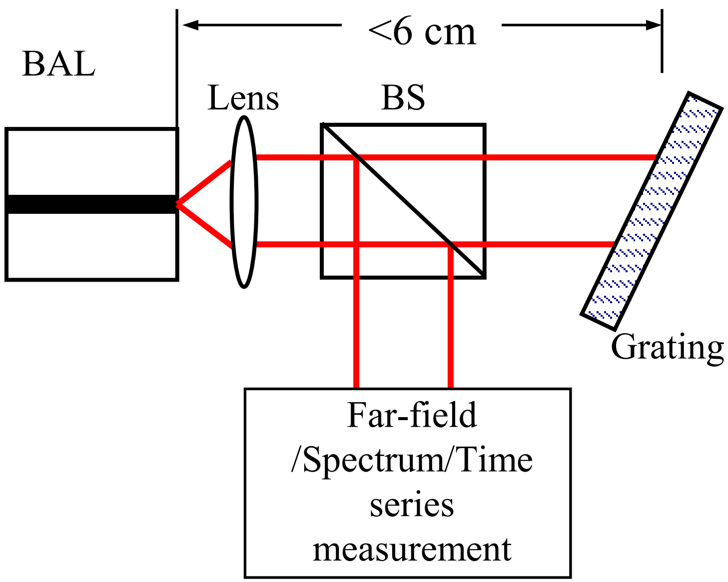
Spectrum of Nanosecond Pulses



Linewidth in enhanced more than 4 times!

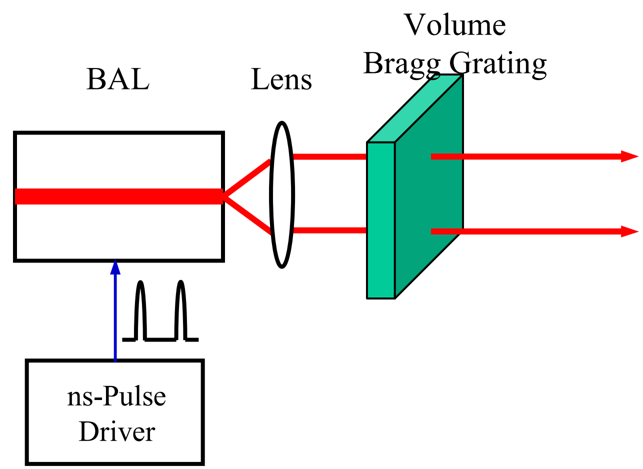
Locking Nanosecond Pulses with External Cavity

Experimental Scheme



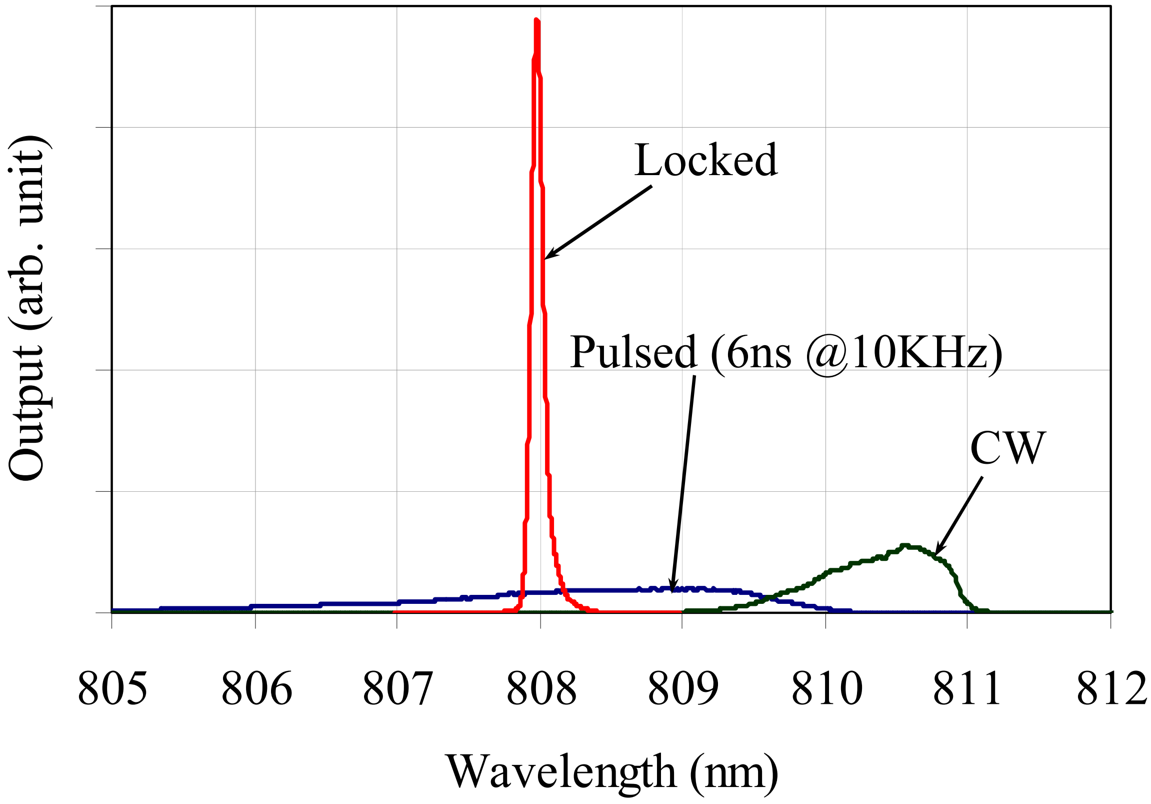
When the laser is operated at a pulse mode, about 50% of the laser output was collimated into a 50 μm-core optical fiber.

Compact Package Using VBG



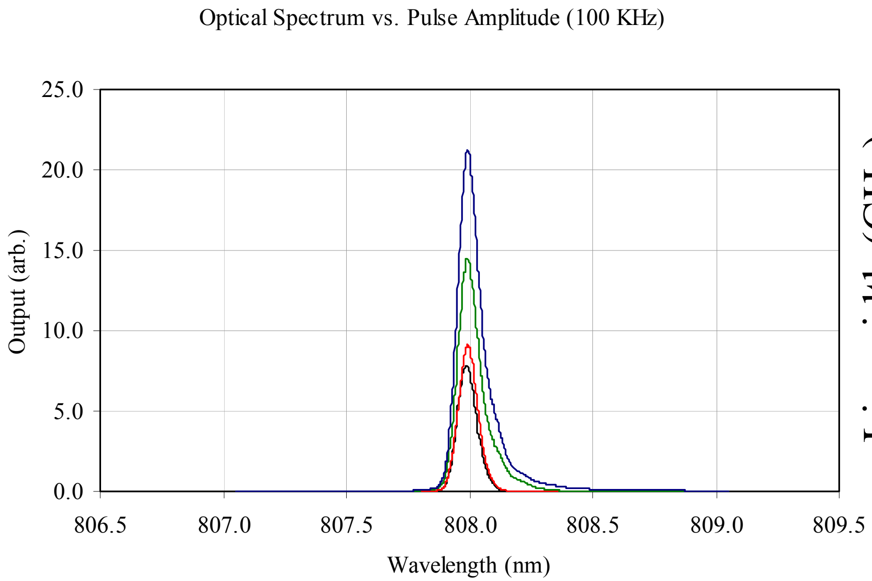
External cavity length: < 5 mm

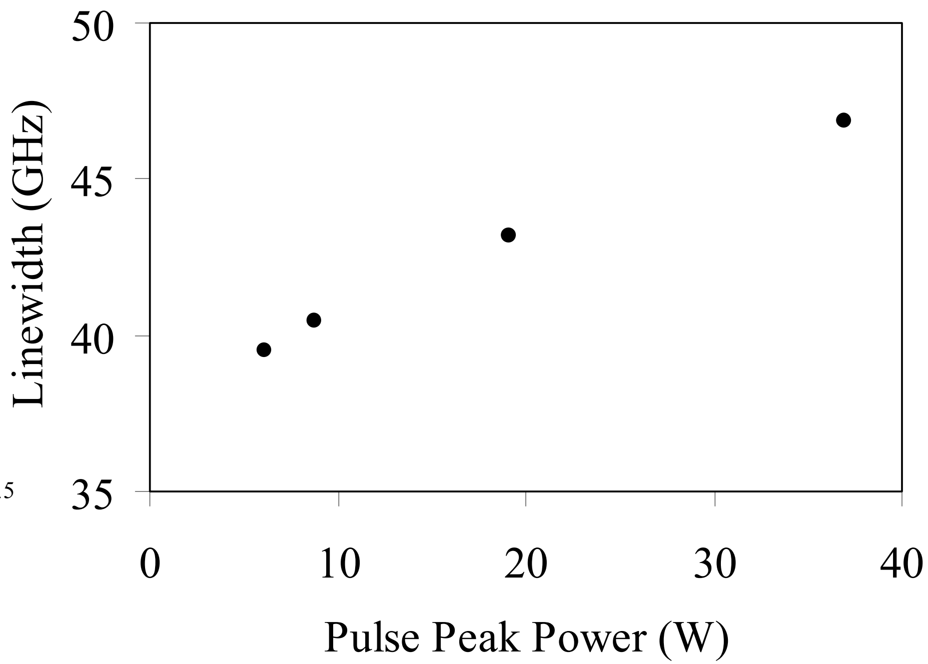
Spectrum of Locked Nanosecond Pulses



Linewidth is reduced from 5 nm to less than 0.1 nm!

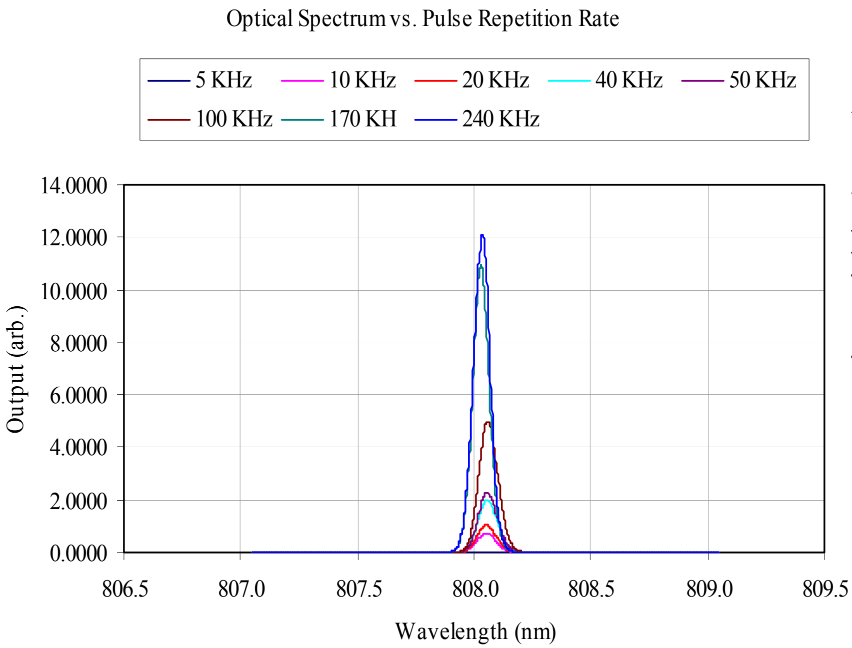
Linewidth Dependence on Peak Power

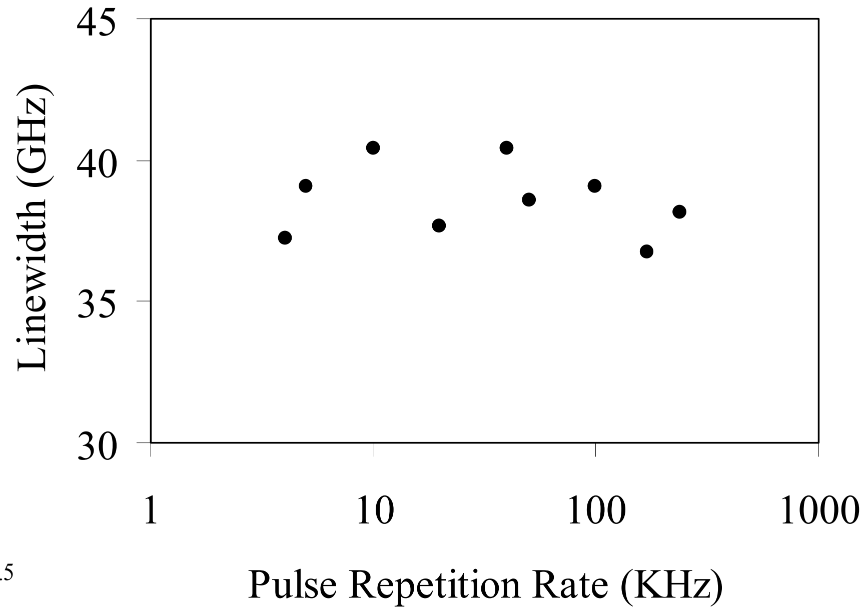




Linewidth linearly depends on pulse peak power

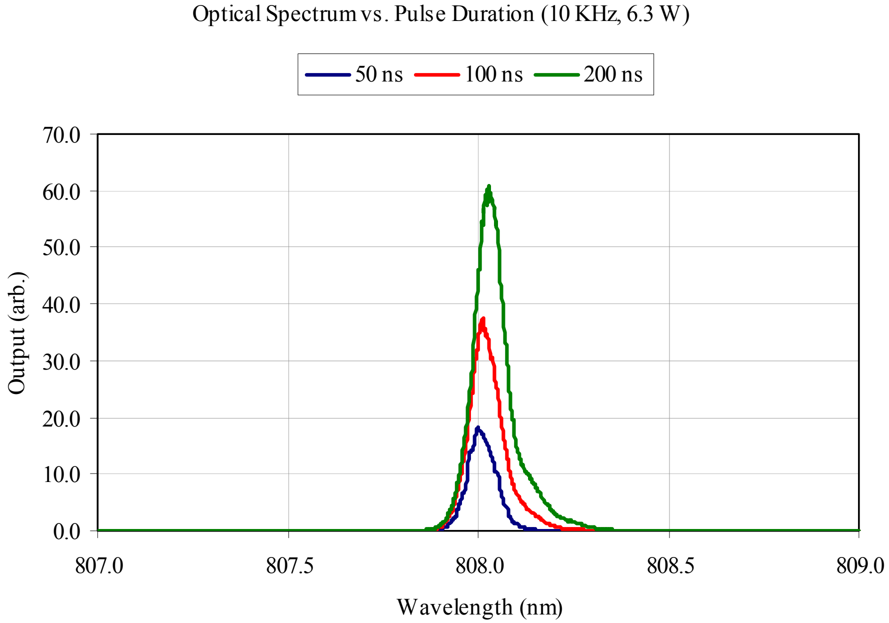
Linewidth Dependence on Repetition Rate

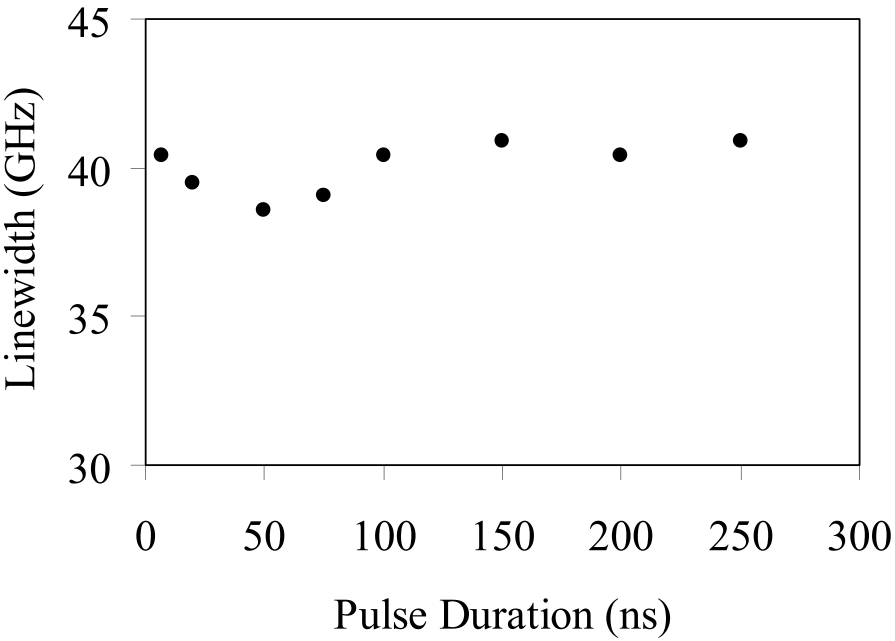




Linewidth does not show monotonic dependence on pulse repetition rate

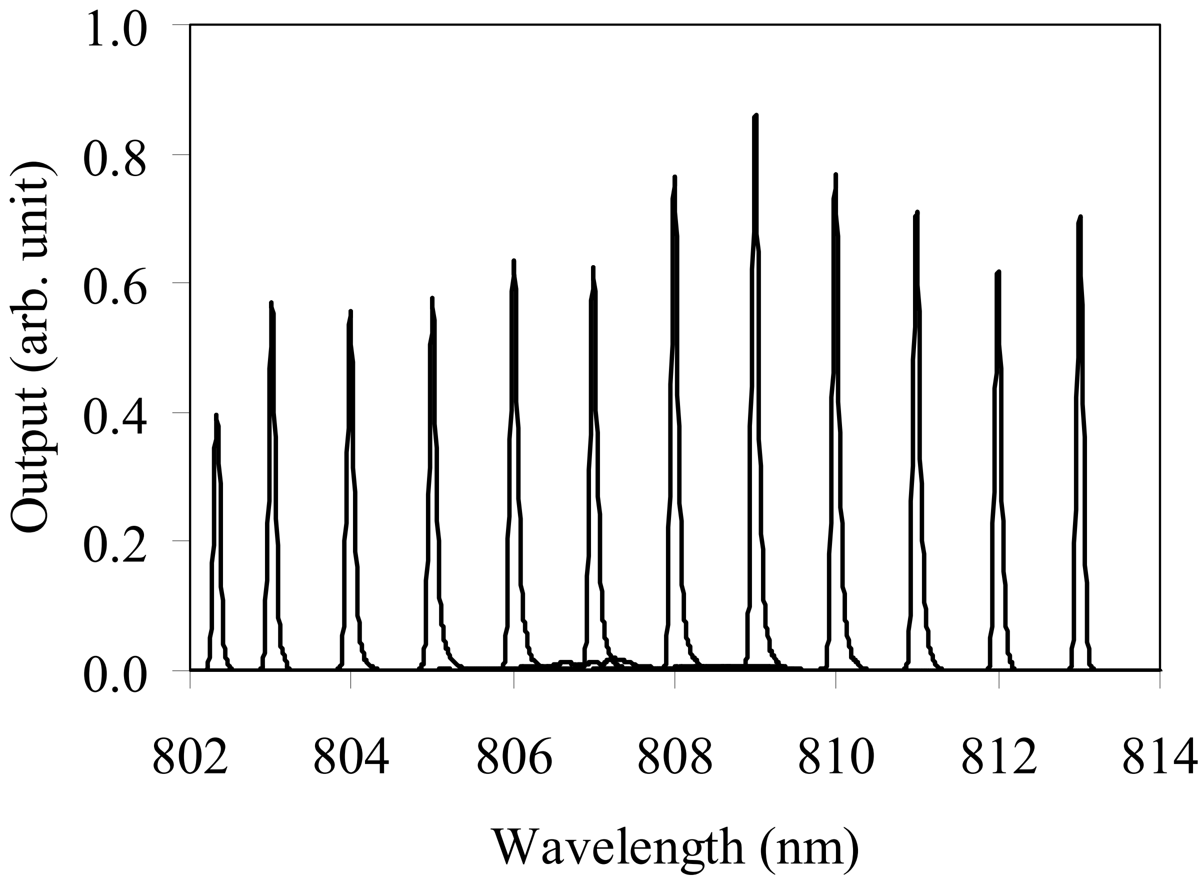
Linewidth Dependence on Pulse Duration





Linewidth does not show monotonic dependence on pulse duration

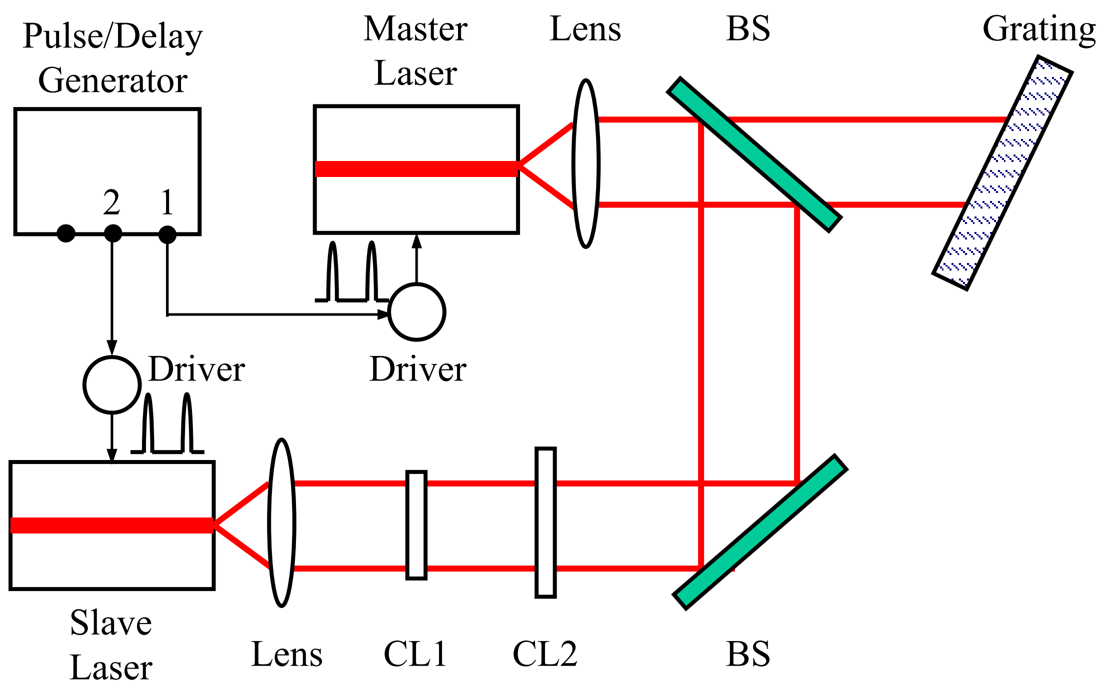
Wavelength Tuning



Wavelength tuning range >10 nm without significant spectrum/waveform changes

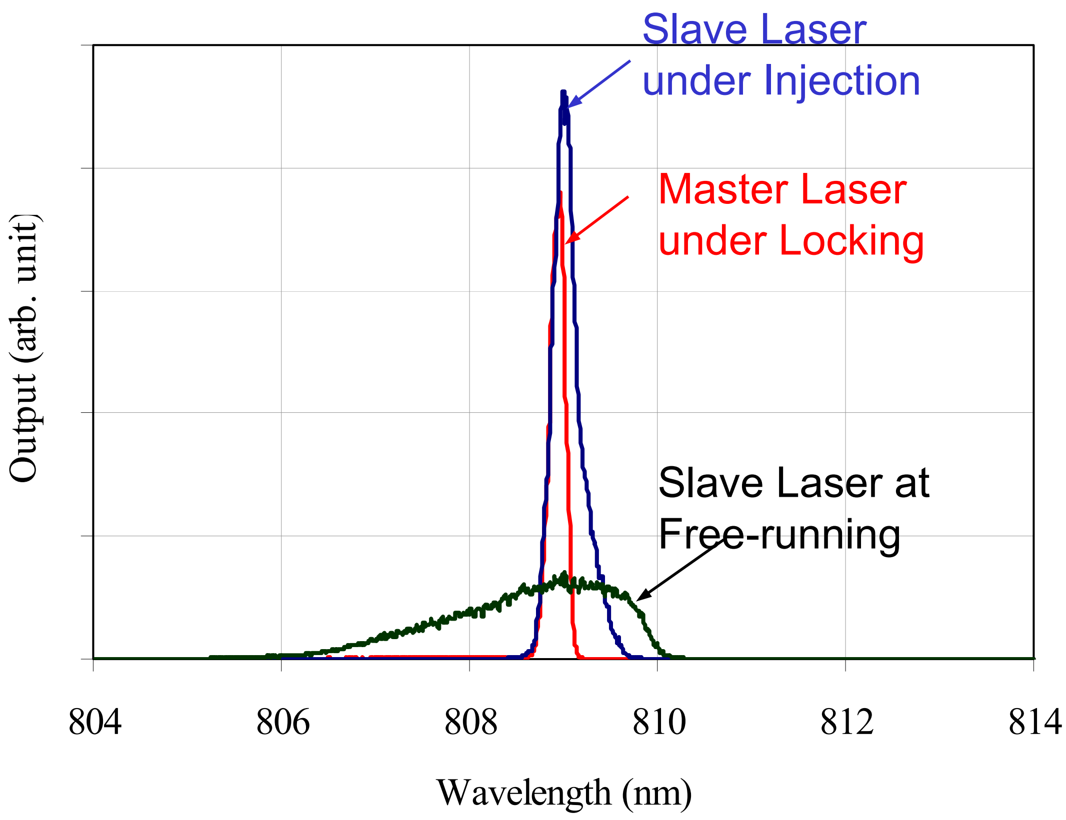
Synchronizing Pulsed Laser Array

Experimental Scheme



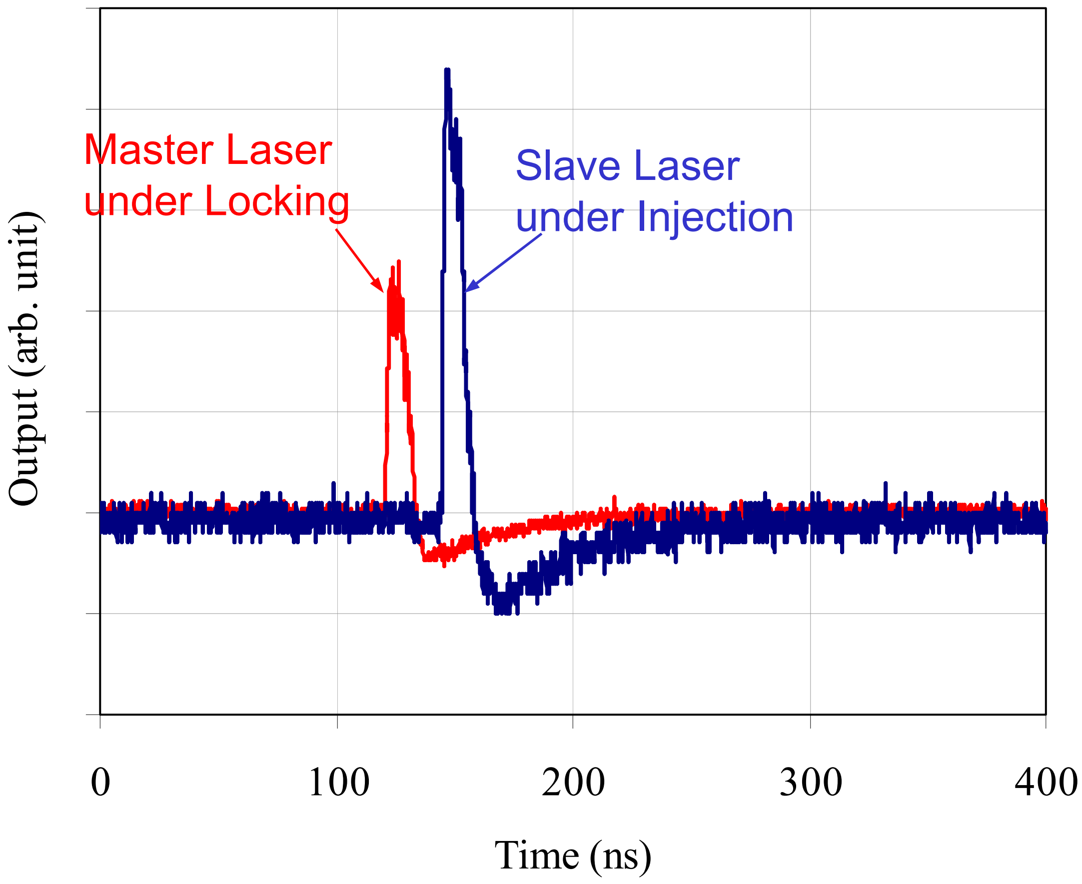
Pulse timing (pulse duration and repetition rate) of master and slave lasers is synchronized with electrical circuitry;
Pulse phase (time delay) is adjusted to guarantee the unidirectional coupling.

Synchronized Pulsed Lasers



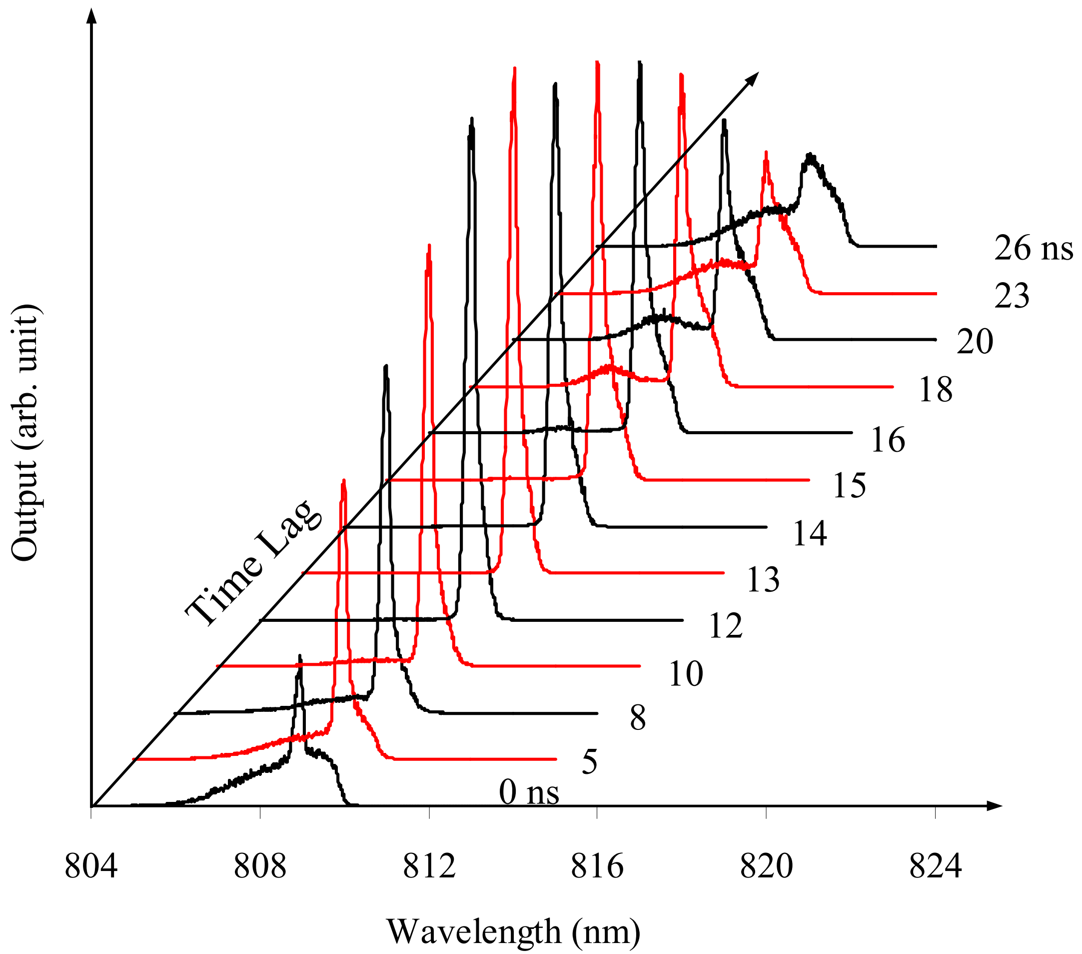
Synchronized spectrum of master and slave pulsed lasers

Synchronized Pulsed Lasers



Temporal waveforms of master and slave pulsed lasers

Synchronization Performance



Synchronization occurs at certain time lags!

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

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

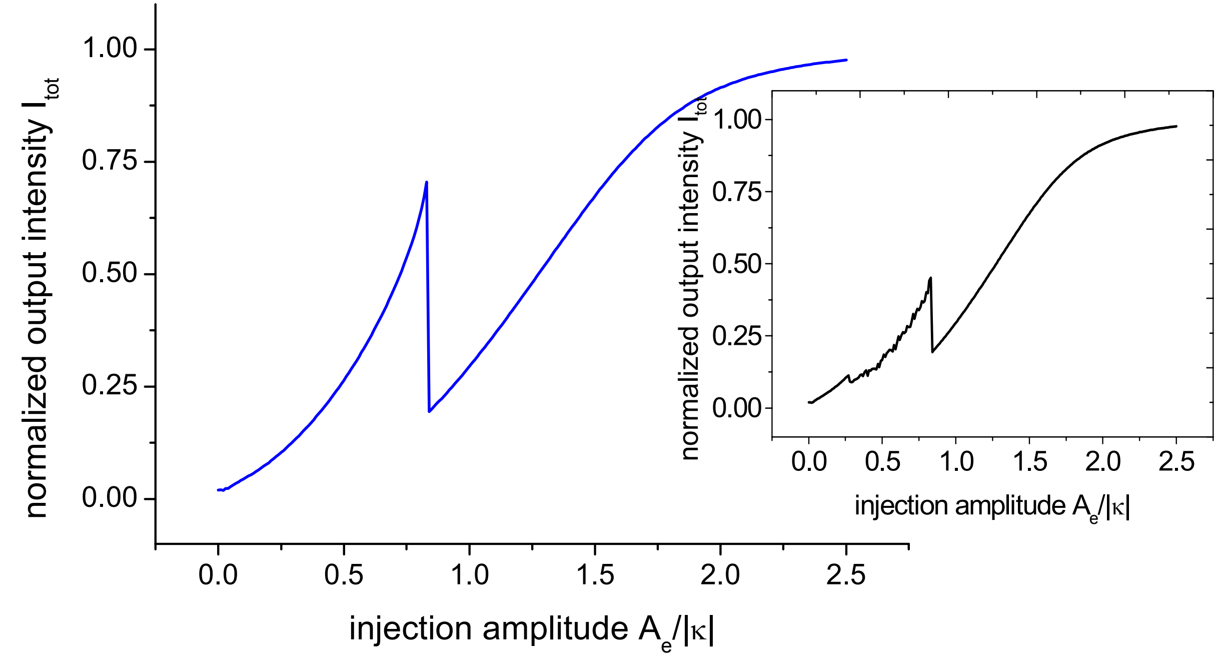
$$f'(\phi) = -2\kappa \cos\phi_c - A_c \cos\frac{\phi_c}{2} = 0$$

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

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

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

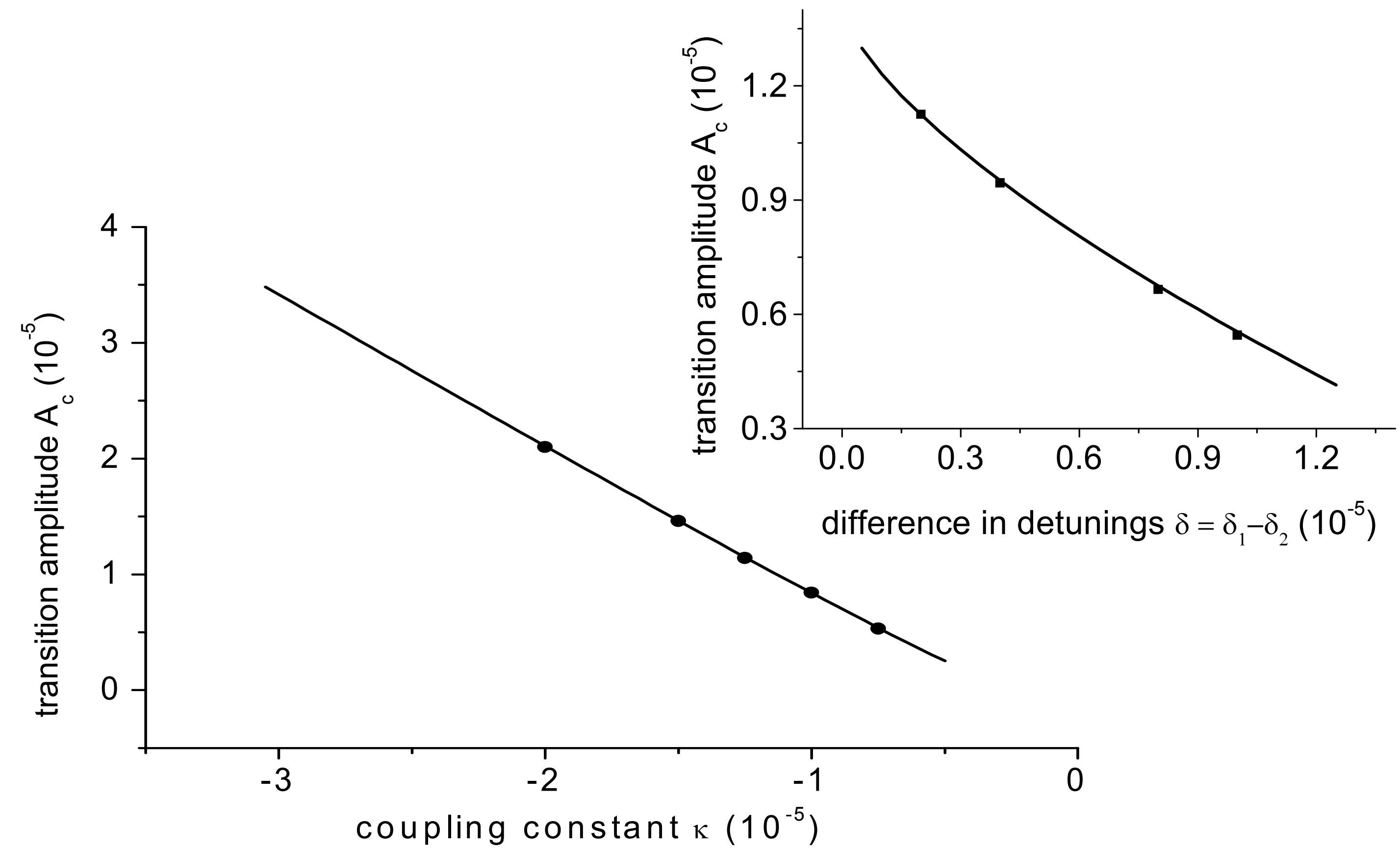
Nonmonotonicity



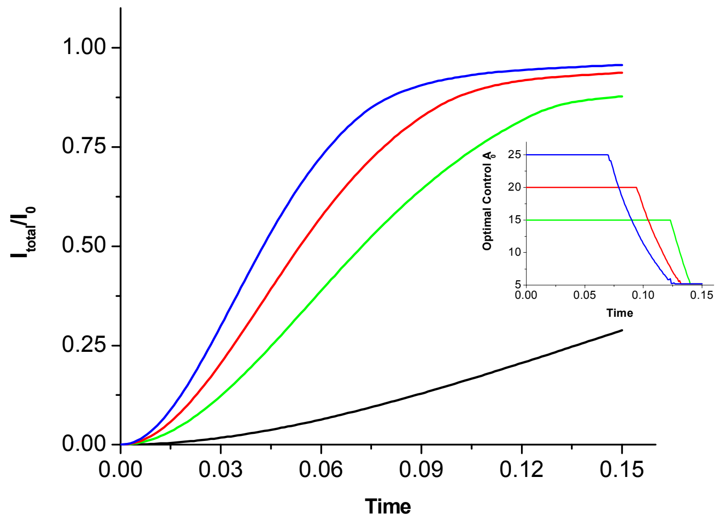
$$A_c = -2\kappa \frac{1-z^2}{\sqrt{1+z^2}}.$$

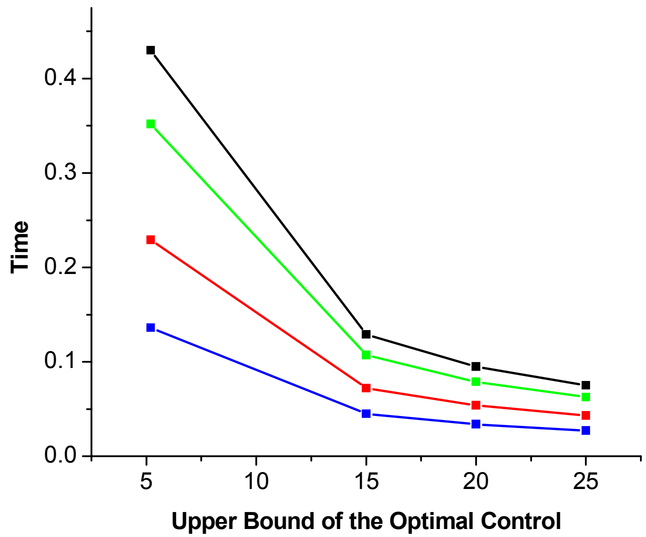
A. I. Khibnik, Y. Braiman, V. Protopopescu, T. A. B. Kennedy, and K. Wiesenfeld, Phys. Rev. A 62, 063815 (2000).

Comparison of the Analysis with Numerical Simulations



Optimal Control of the Transient Behavior





E. Jung, S. Lenhart, V. Protopopescu, and Y. Braiman, Phys. Rev. E **67,** 046222, (2003).

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

CESAR
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