Synchronization of High Power Laser Arrays

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Center for Engineering Science Advanced Research
Computer Science & Mathematics Division
Oak Ridge National Laboratory

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1. Synchronization of
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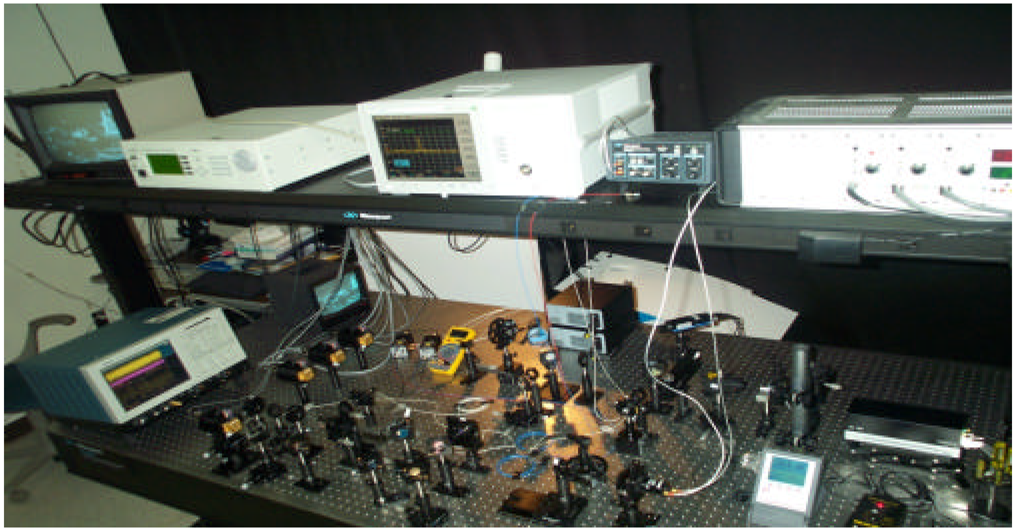
2. Synchronization of Pulsed
   Semiconductor Laser Arrays
3. Quantum Teleportation
4. Quantum Optics



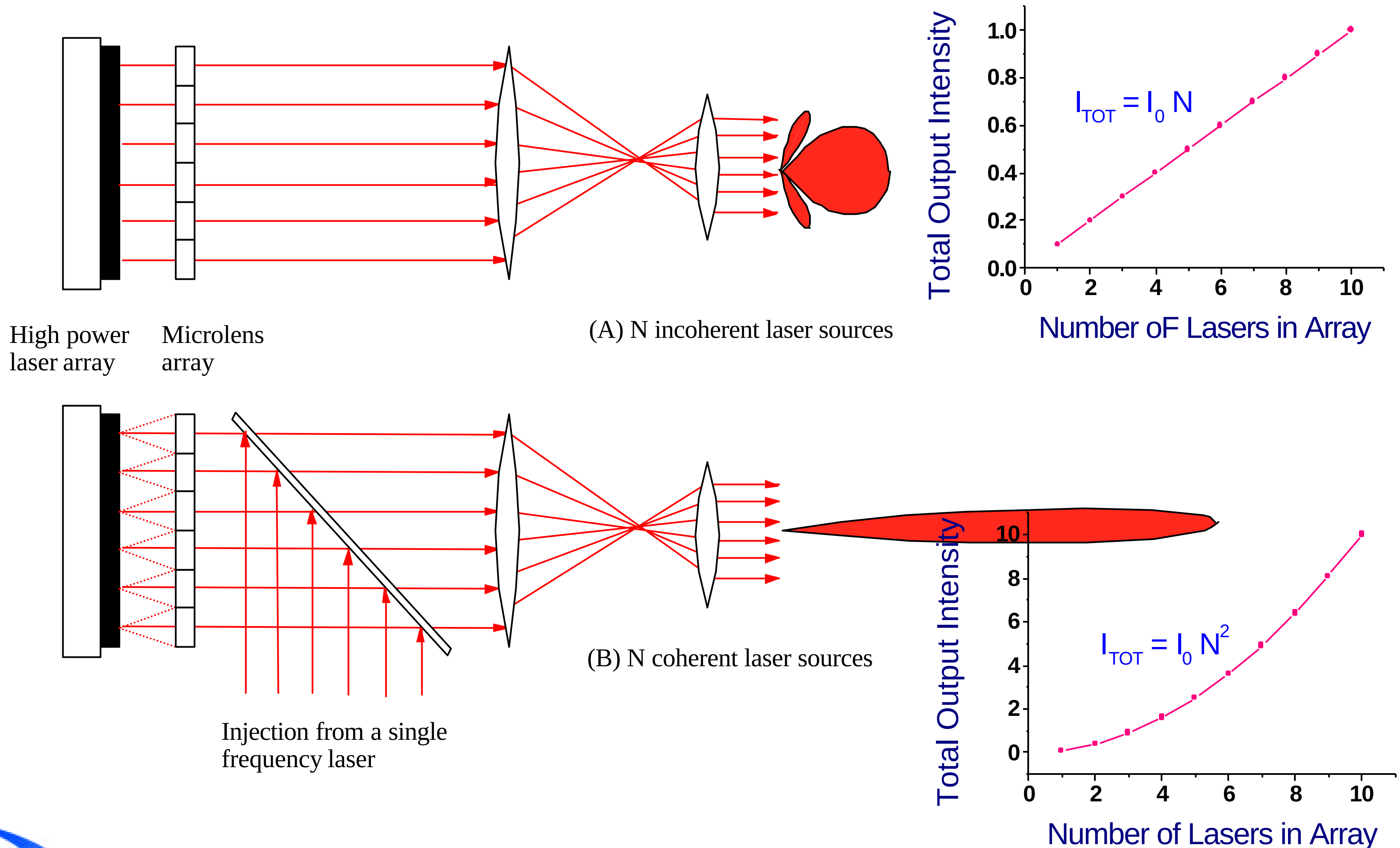
People

Experiment: four full time + two part time

Theory/Computation: four full time theorists + one part time

External Participation/Collaboration - a group of Raj Roy (UMD, College Park)

N^2 Effect


High power laser array
Microlens array
(A) N incoherent laser sources
Total Output Intensity
1.0
0.8
0.6
0.4
0.2
0.0
0
2
4
6
8
10
Number oF Lasers in Array
$I_{TOT} = I_0 N$
(B) N coherent laser sources
Injection from a single frequency laser
Total Output Intensity
10
8
6
4
2
0
0
2
4
6
8
10
Number of Lasers in Array
$I_{TOT} = I_0 N^2$

Laser Array Synchronization

$$?_j(t) = E_j \exp(-iw_j t) + cc$$

$$I(t) = |\sqrt{I_0}\exp(if_1) + \sqrt{I_0}\exp(if_2) + \dots|^2$$

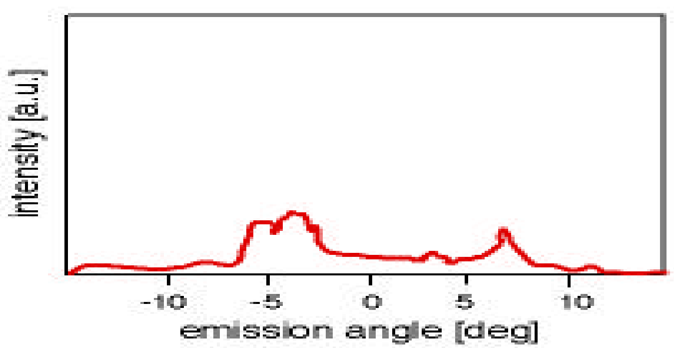
E_j - complex amplitude

ω_j - the frequency

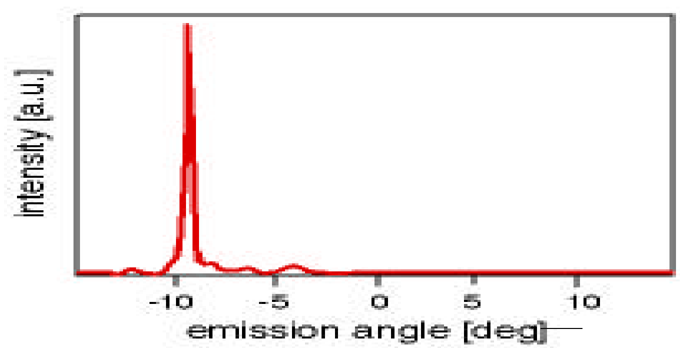
$$E_j = \sqrt{I_j}\, e^{if_j}$$

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

$\Rightarrow I \sim N^2 I_0$



Noncoherent addition



Coherent addition

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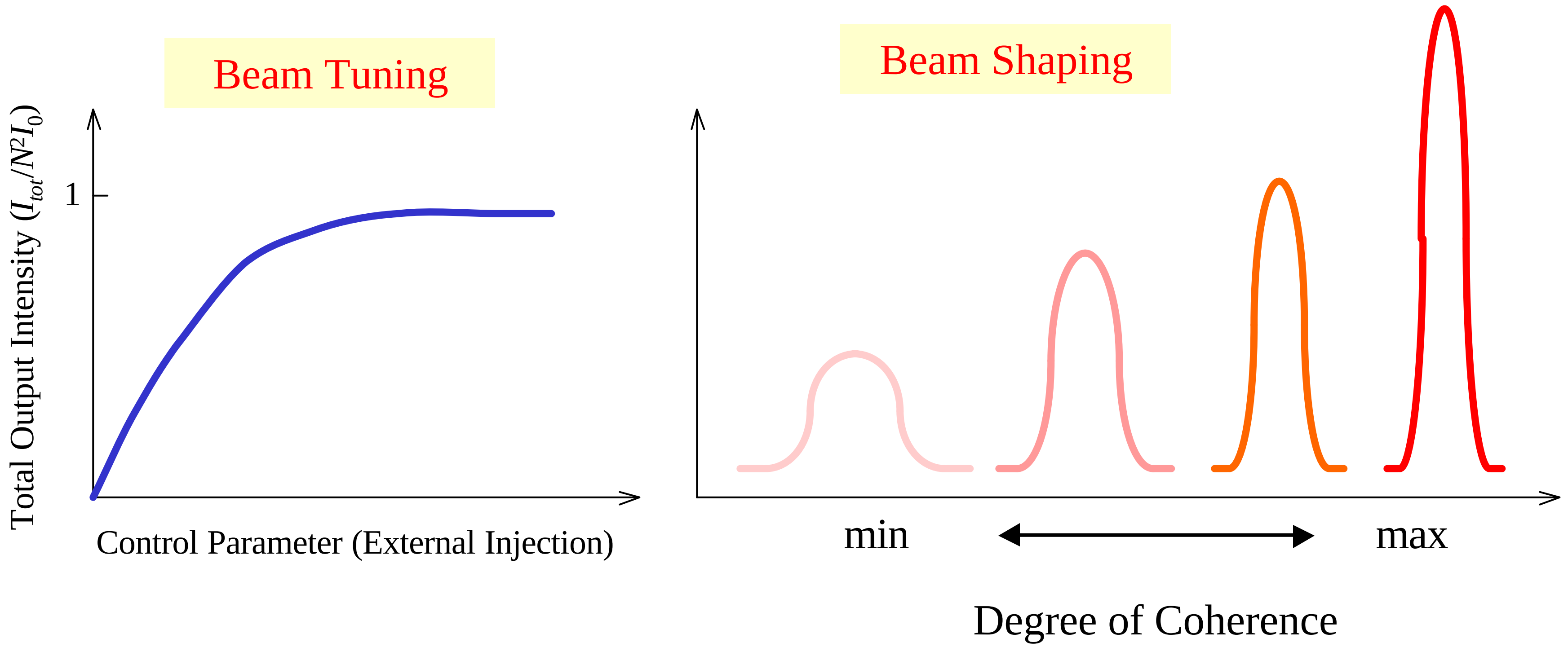
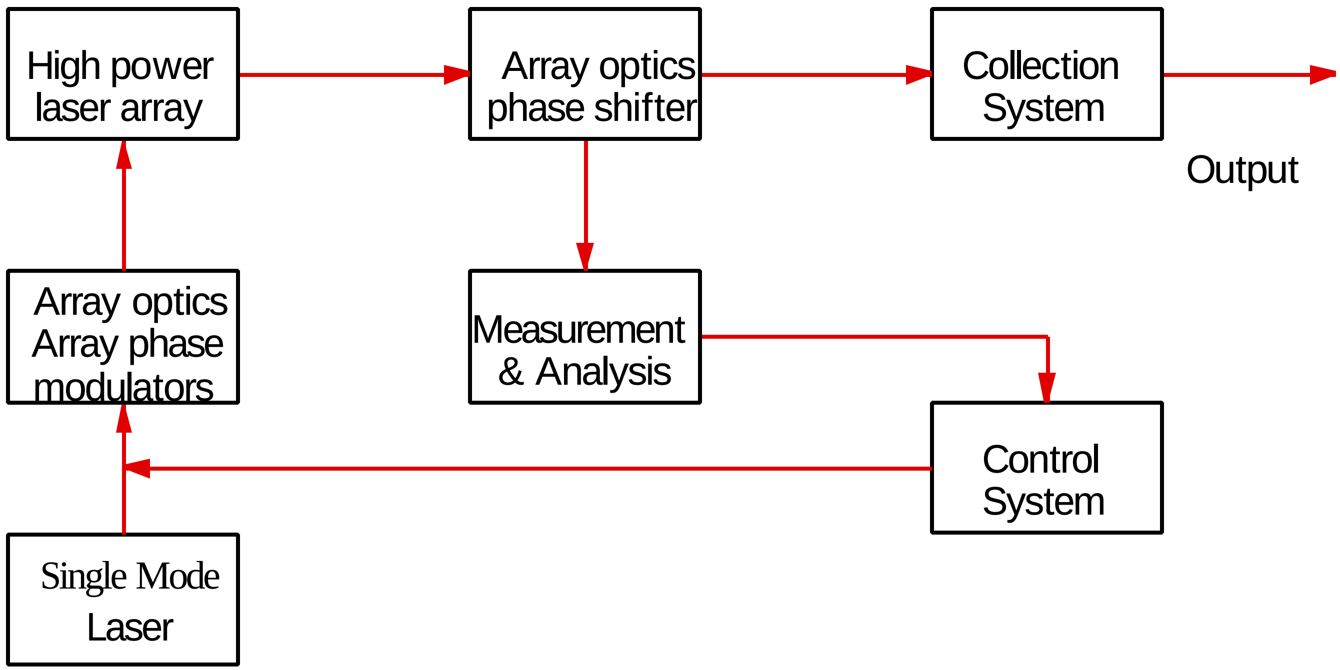
Benefits of this Concept

- **High intensity coherent light source (Potential of orders of magnitude increase in irradiance).**
- **Ability (a) to control the shape and the intensity of the beam and (b) to steer the beam in a given direction**
- **High speed , high power, and high contrast data transmission for communication (in Gbps rate).**

Beam Properties



Injection Experiment



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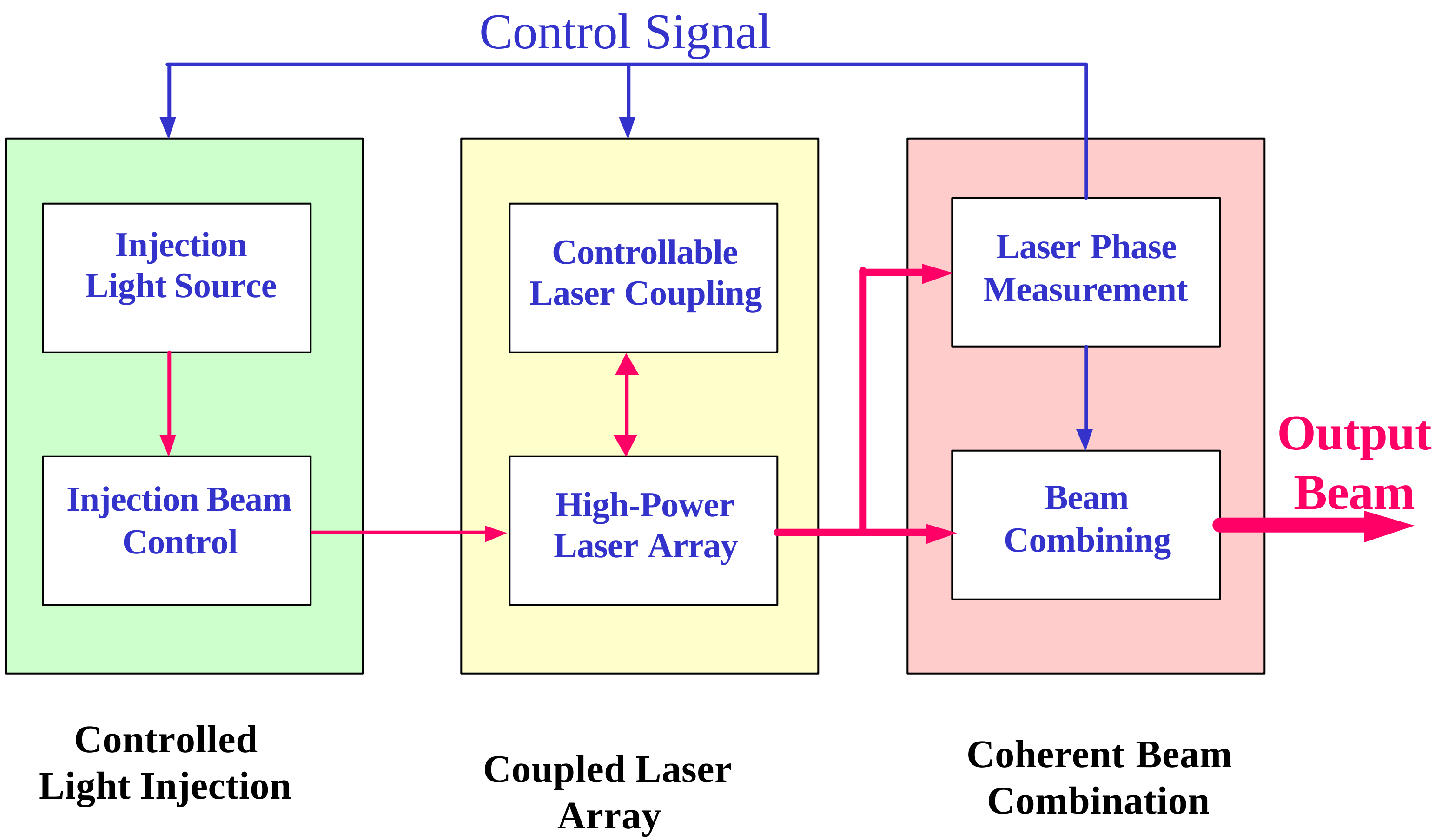
Dynamical Synchronization of High-Power Laser Arrays



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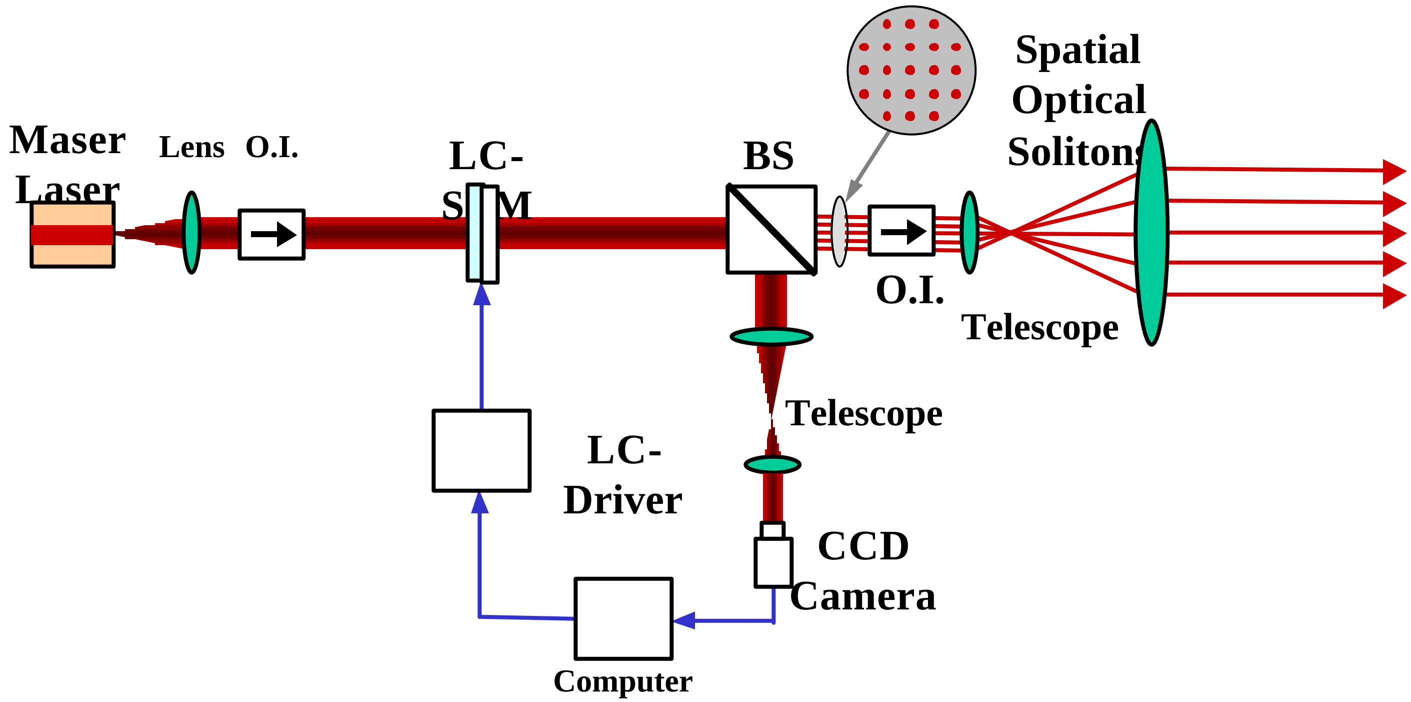
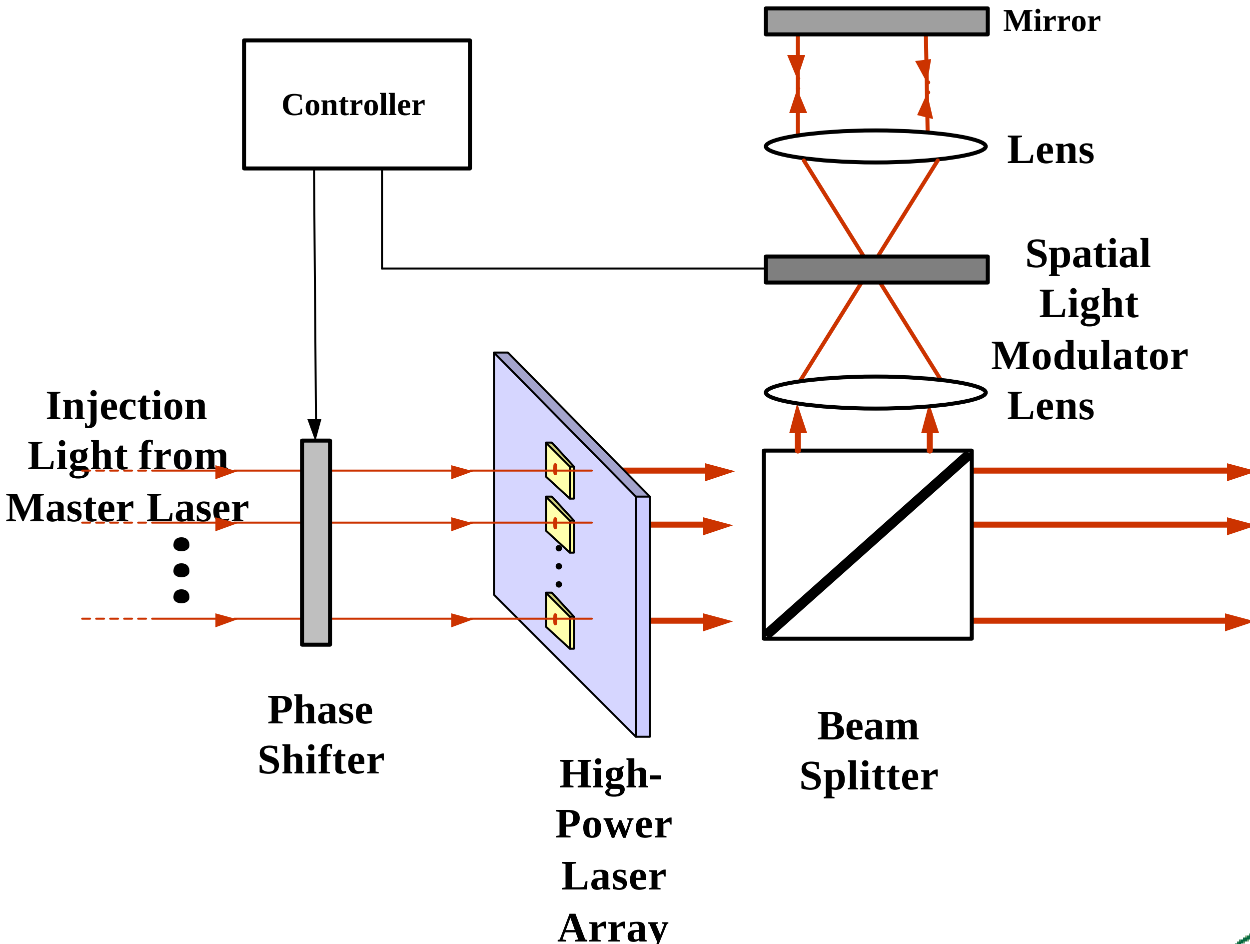
Key Technical Element I:
Scalable Injection Beam Splitting



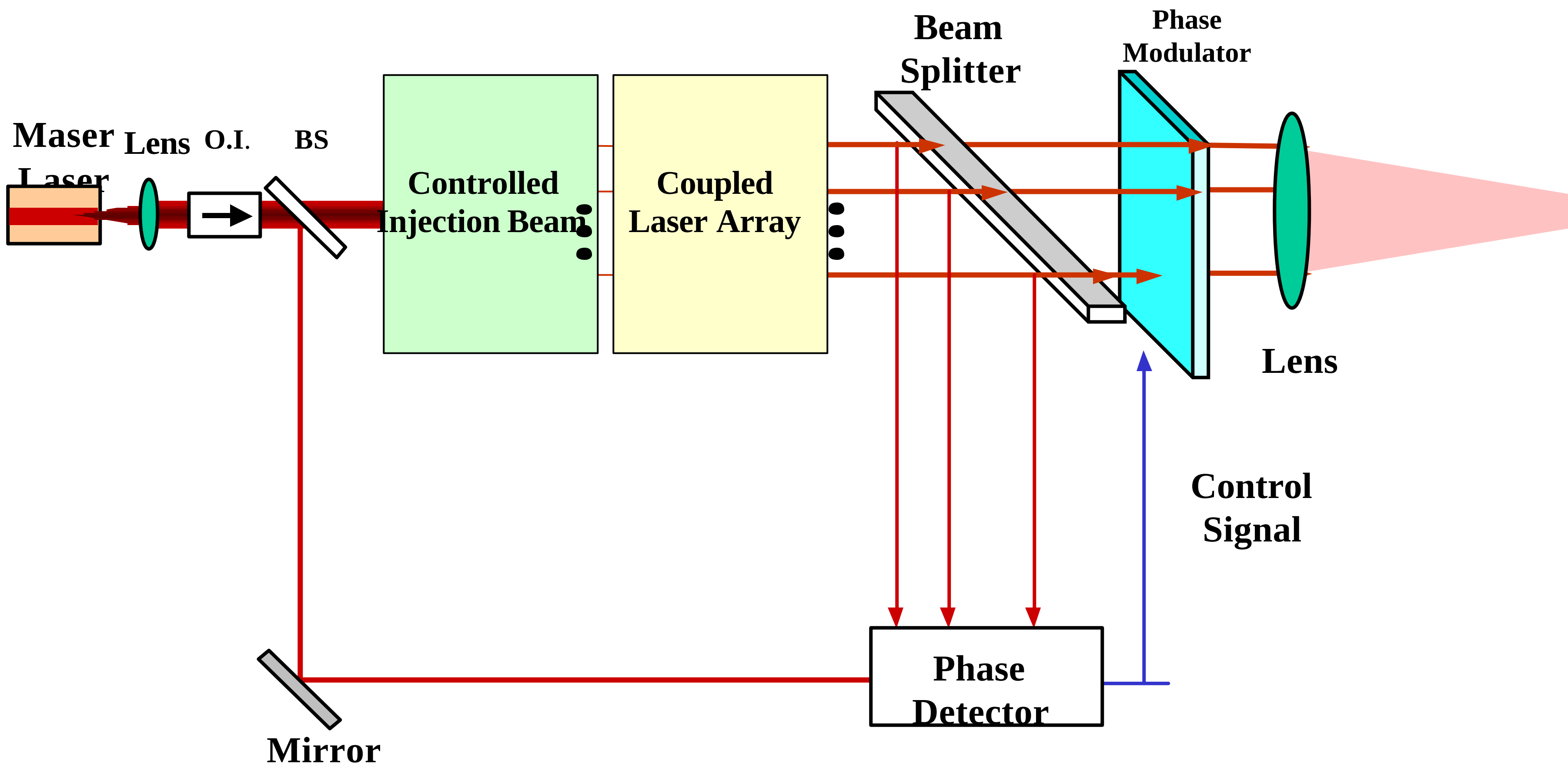
BS: Beam splitter, O.I.: Optical isolator, LC-SLM: Liquid crystal spatial light modulator

Reference: Vorontsov et al, *J. Opt. Soc. Am. B* 17, 266 (2000).

Key Technical Element II: Controllable Coupled Laser Array



Key Technical Element III: Coherent Beam Combination



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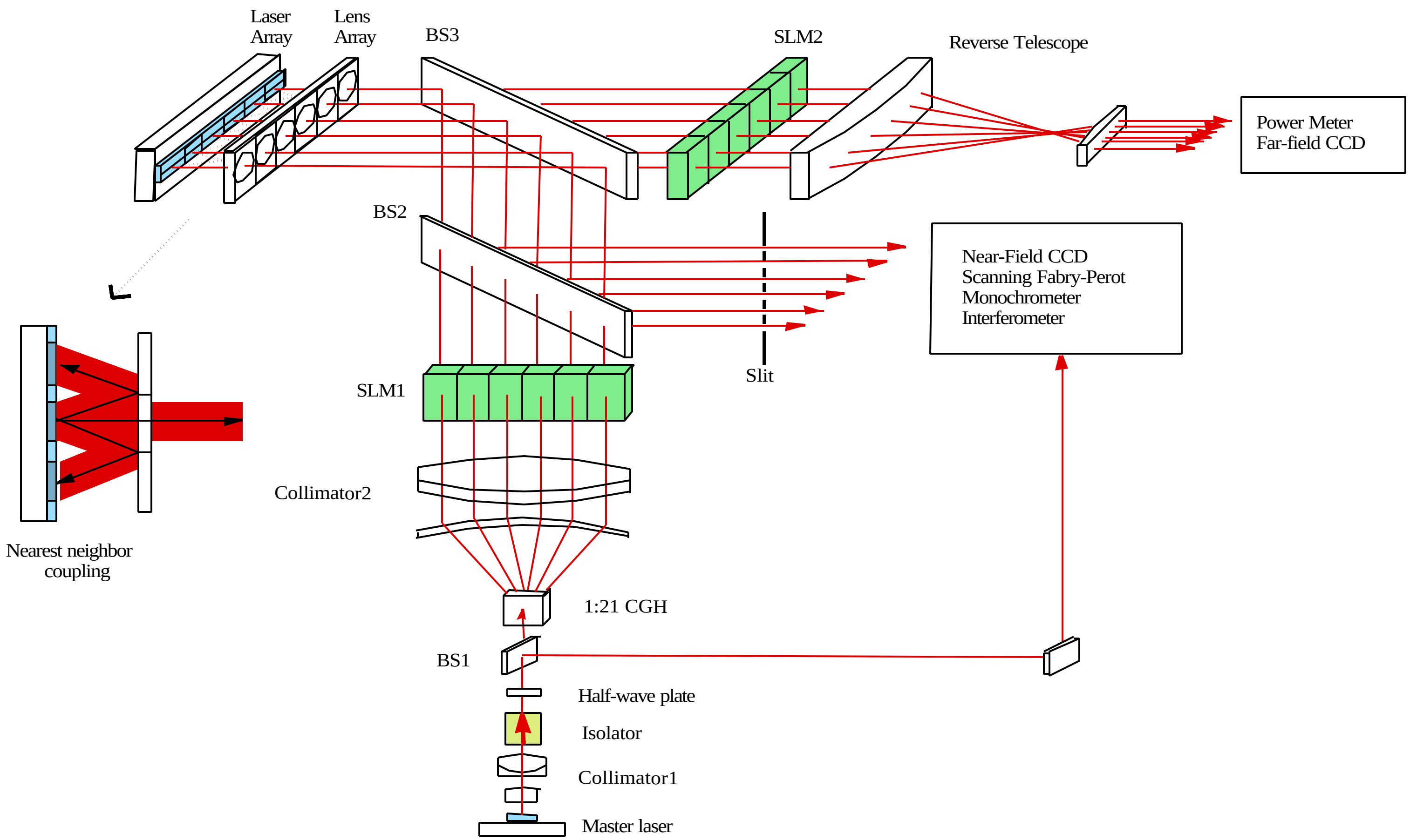
Schematic Design



CGH __ Computer Generated Hologram, SLM __ Spatial Light Modulator, BS __ Beamsplitter

Coherence Control of Laser Array

- **Why coherence control?**
  - Single mode operation
  - High beam quality
- **Condition for coherent beam coupling**
  - Frequency locking
  - Phase locking
- **How ?**
  - Optical injection
  - External mirror/grating

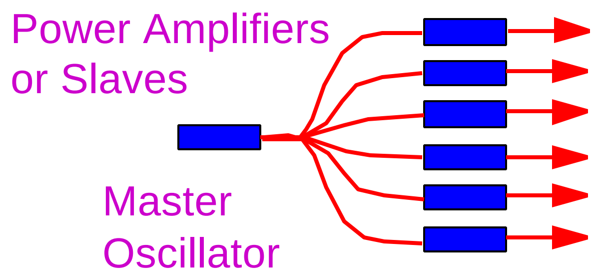
Challenges

- **Beam injection into each laser - achieve controlled injection**
- **Phase locking the array and stability- though lasers are almost identical, the desired *in-phase state is unstable* for a broad range of parameters**
- **Beam collection - fusing outcoming beams without losing phase coherence**

Commonly Used Array Architectures

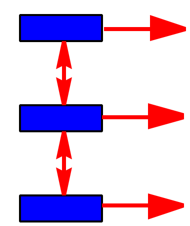
MOPA/Injection Locking

Single, stable mode from master oscillator

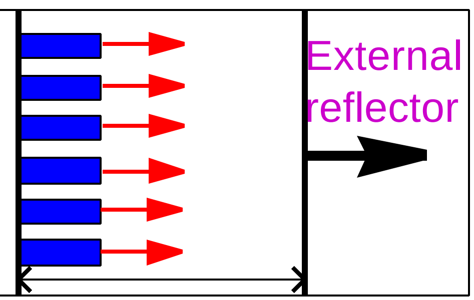


Coupled Oscillators

Evanescent or Leaky Wave-coupled (side by side)
Longitudinally coupled (end-to-end)



External Cavities



Previous Research on Broad-Area High-Power Semiconductor Laser

Single Broad-Area Laser Diode

Aperture < 100 μm ×1 μm, power: < 1 W

H. Horiuchi et al., *Appl. Phys. B* **68**, 1021 (1999).

Laser Array

Overall array aperture < 100 μm ×1 μm

Total output power < 1.2W

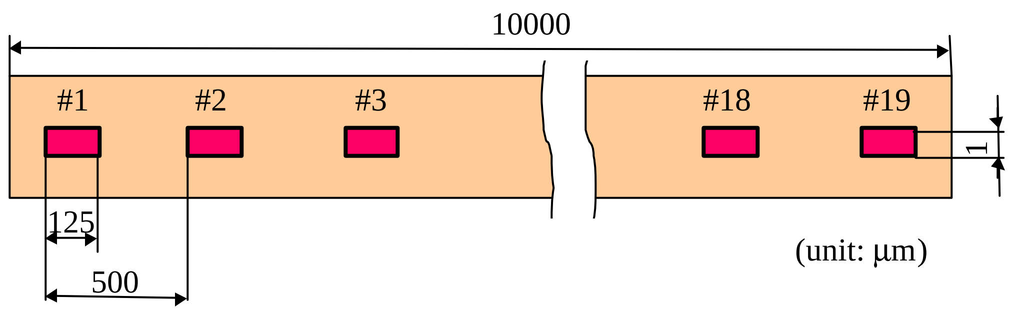
S. MacCormack et al., *Opt. Lett*. **19**, 120 (1994).

H. Tsuchida, *Opt. Lett*. **19**, 1741 (1994).

Our Target

Achieve coherent coupling of a broad-area laser array using optical injection locking.

Commercial Broad-Area Laser Diode Array



Maximum power: >1W (each laser)

Far-field angle: ~ 6×50°

Wavelength: 806~810 nm

Bandwidth: ~ 2 nm

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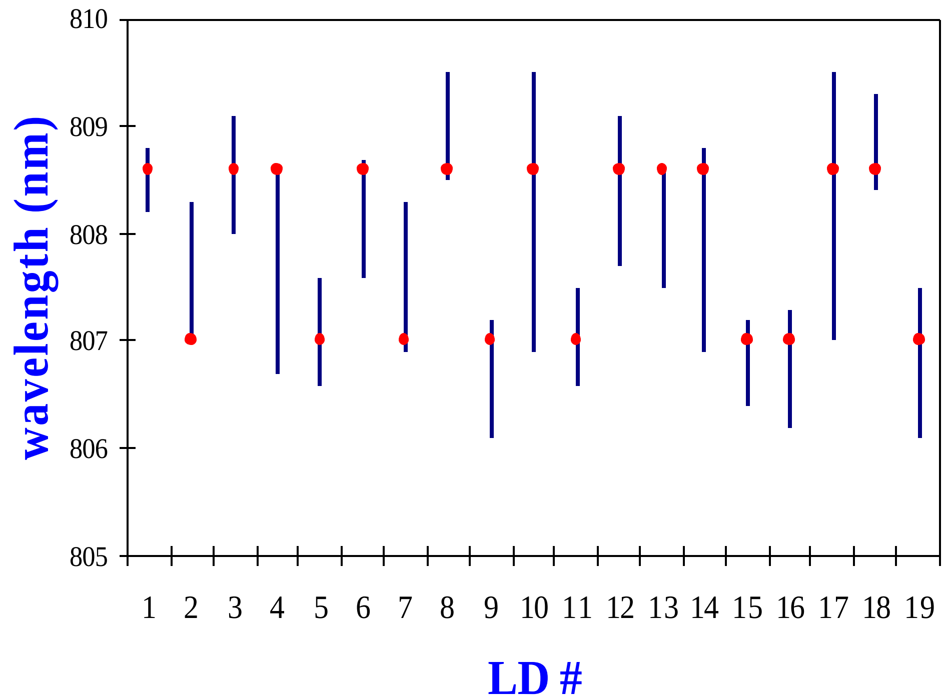
Wavelength Span of all 19 Lasers

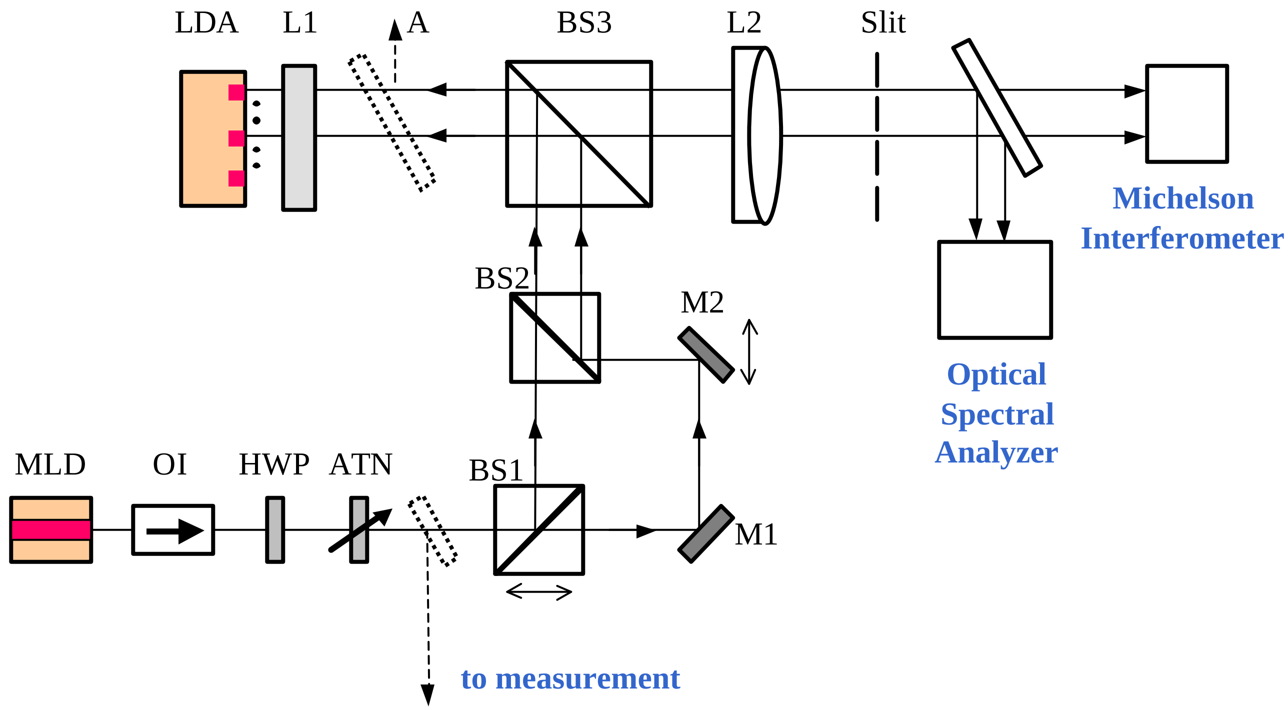
806 < l < 810 (nm)



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

Y. Liu, G. Bitton, P. Cheinet, R. Garrett, H. K. Liu, and Y. Braiman, Proceedings of LASE 2002, High Power Lasers and Applications, SPIE's 14th Annual Symposium (Photonics West), 2002.

Experimental Setup for Injection Locking



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

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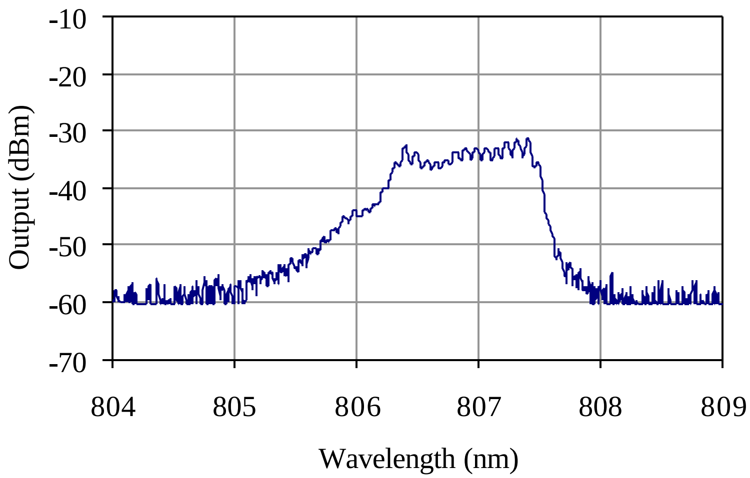
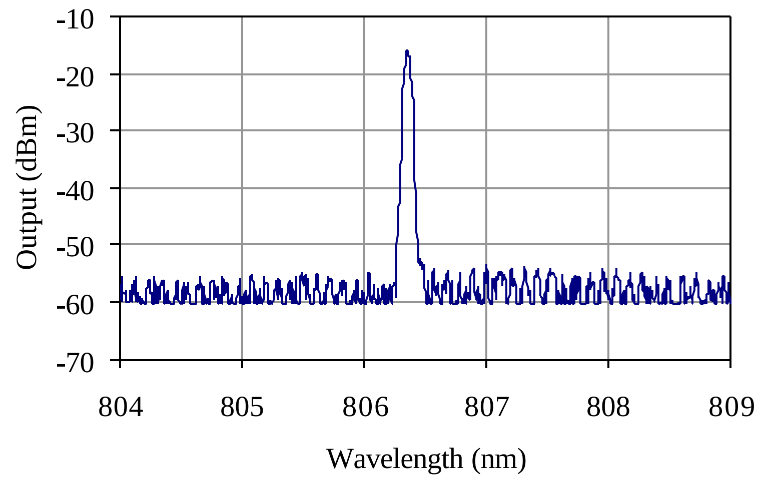
Optical Spectrum

Multimode

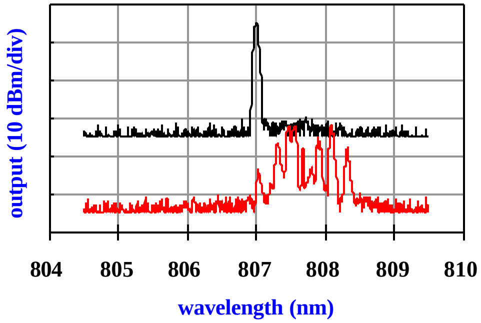


Single Mode

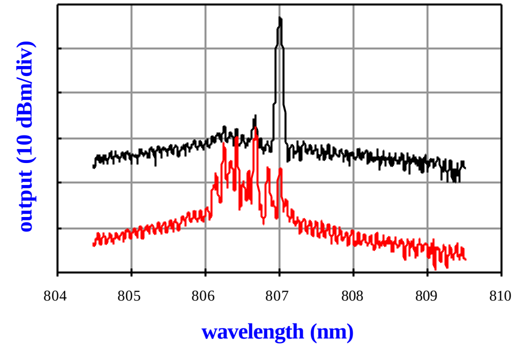


Successful Injection Locking of Individual Lasers

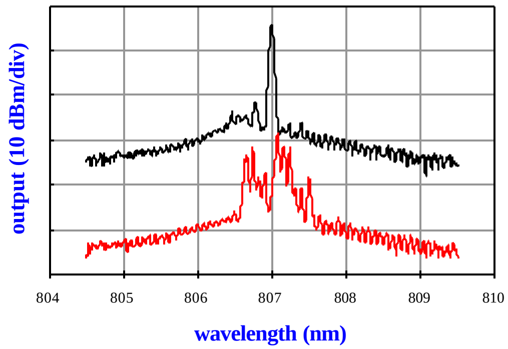
LD#2



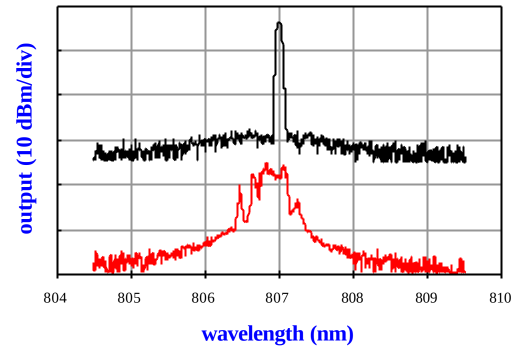
LD#9



LD#11

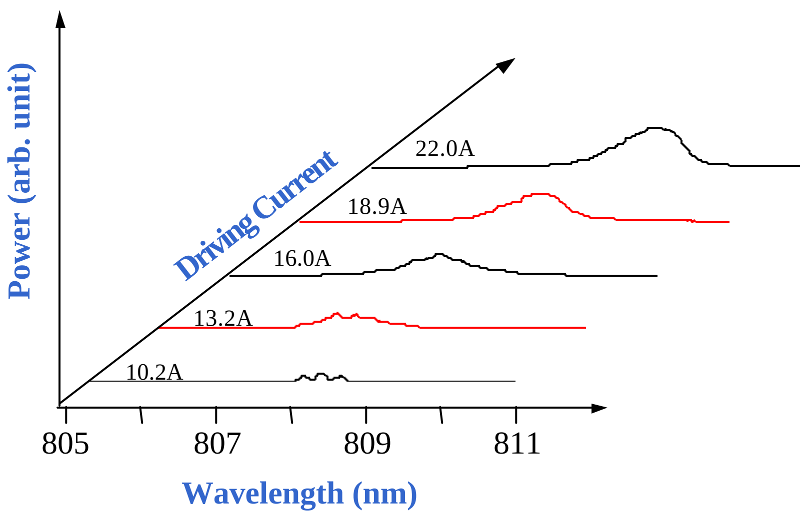


LD#15

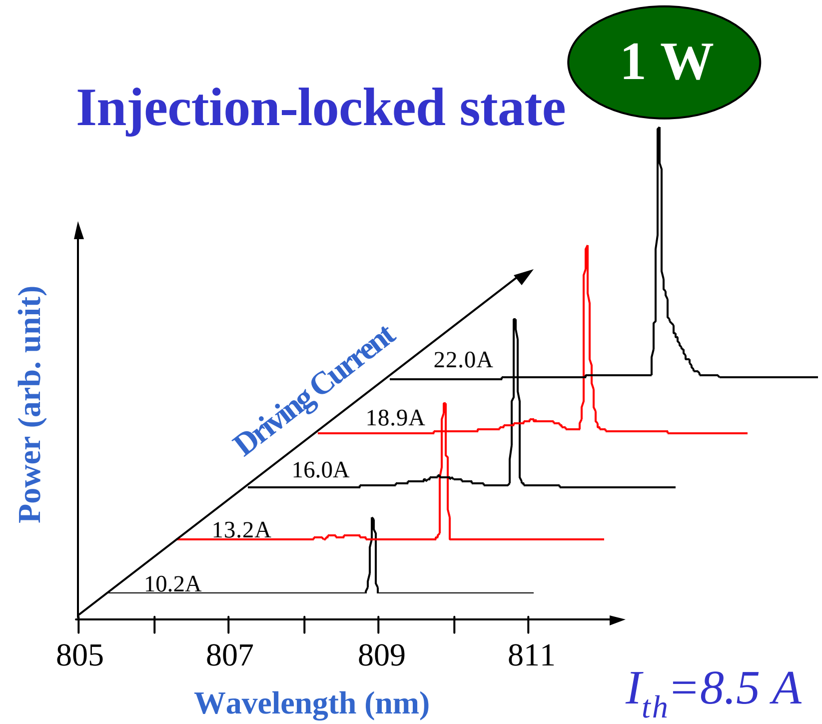


Robustness of Injection Locking

Free-running state



Injection-locked state



Condition for Injection Locking

- Matching Between the Injection and Slave Laser Frequencies
- Less than 0.5 mW of Injection Power !

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Y. Liu, H. K. Liu, and Y. Braiman, Appl. Phys. Lett. 81, 978 (2002)

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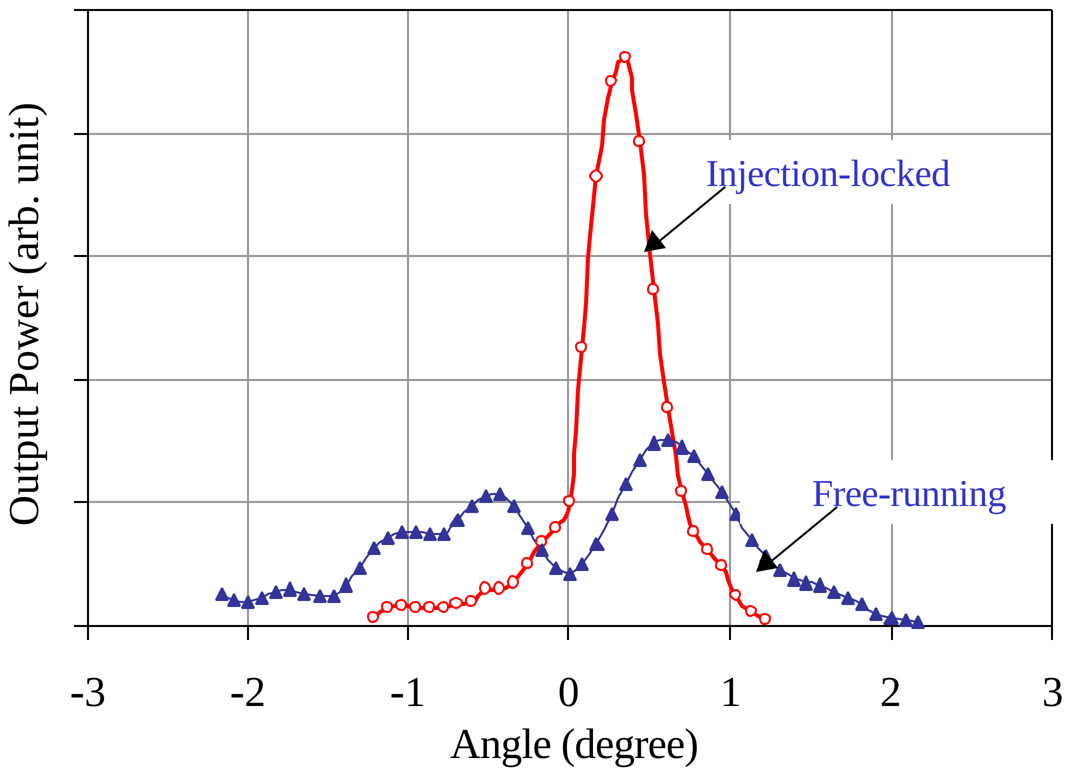
Far-Field Pattern at Injection-Locking



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

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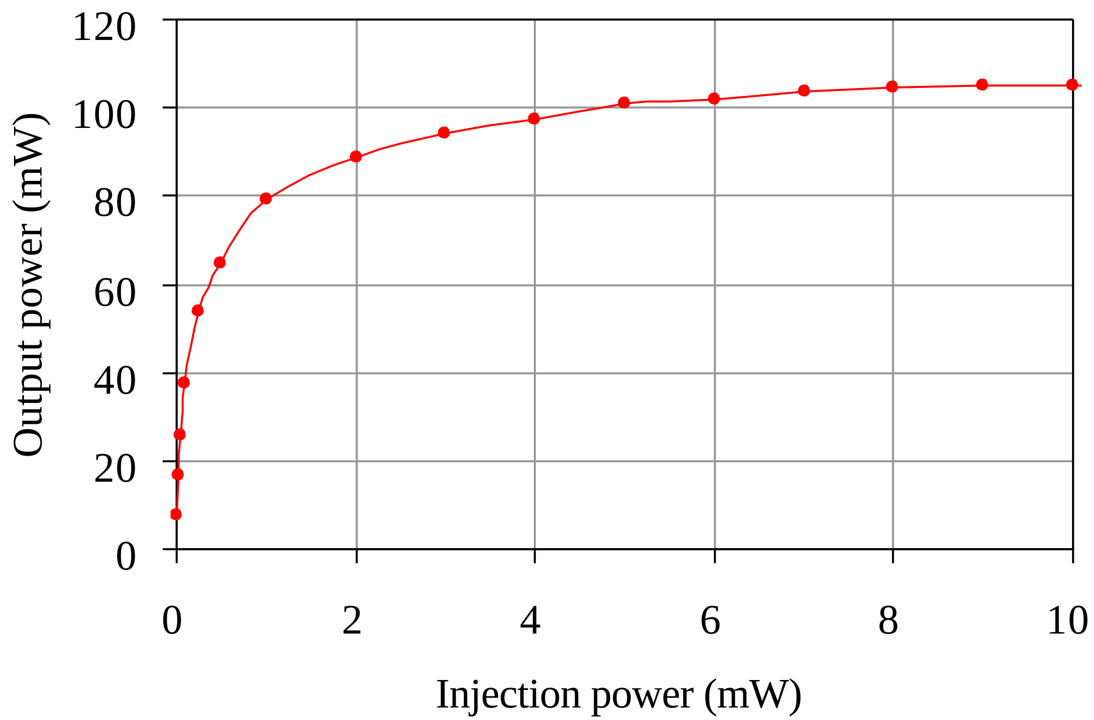
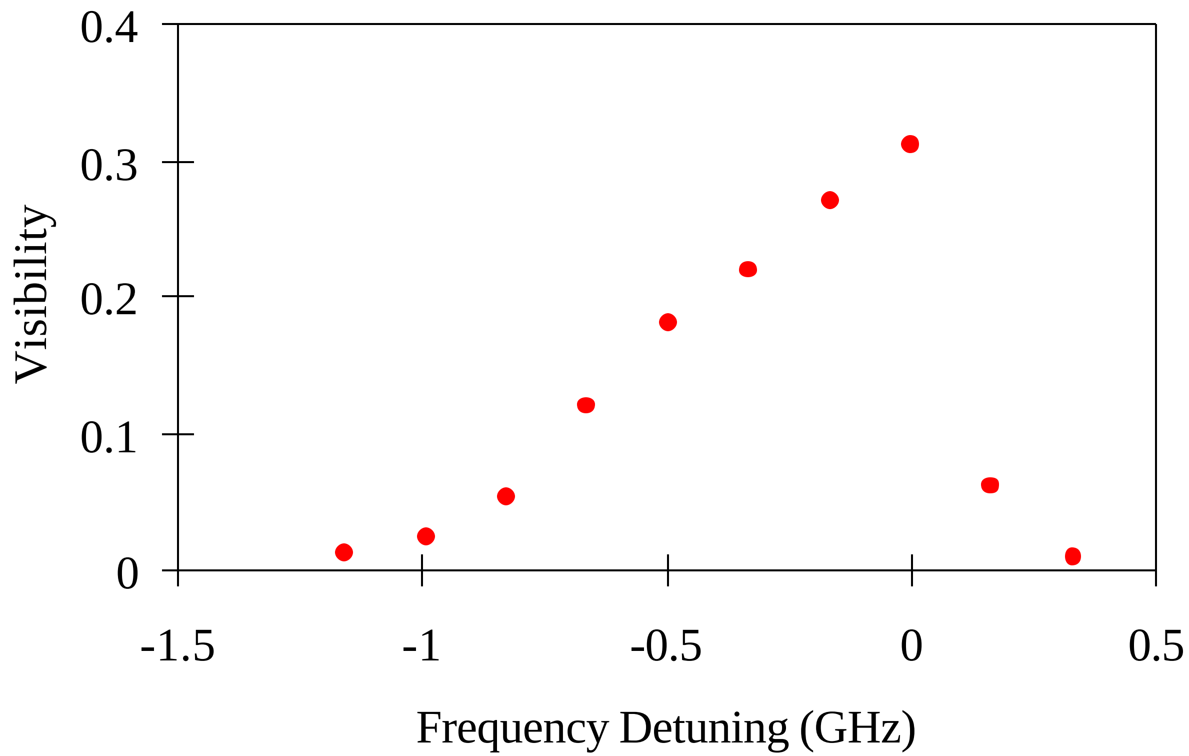
Amplification of Injection Light



I_d=1.3 I_{th}

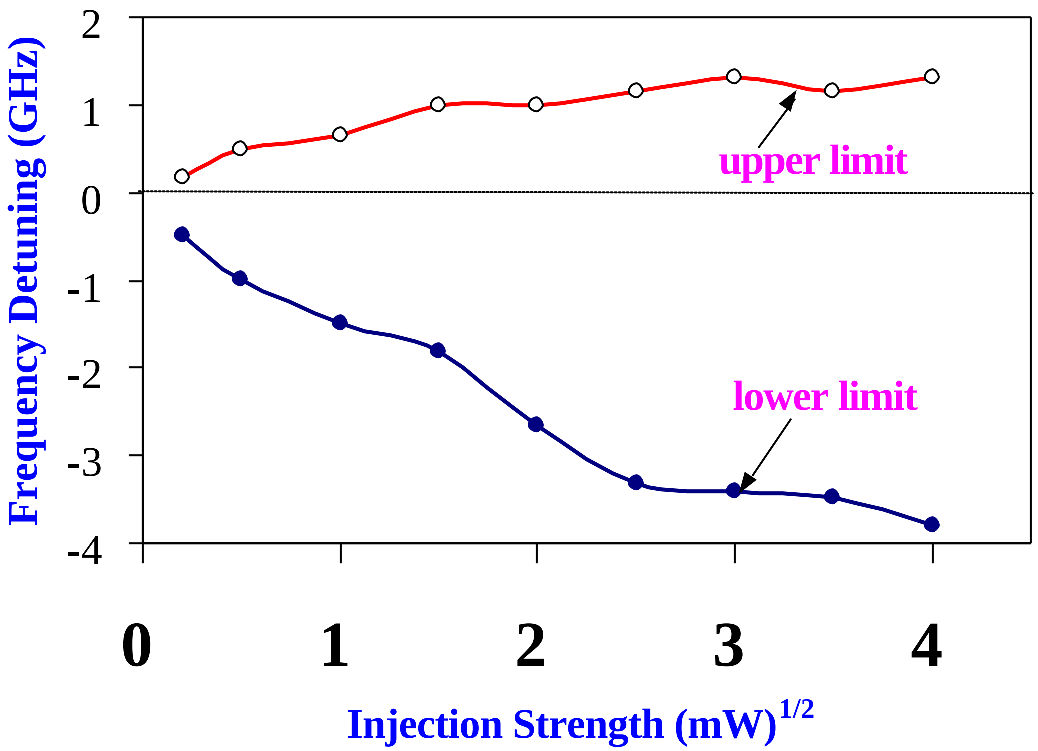
•The output linearly depends on low injection power;
•The output rapidly saturates at high injection power;
•The saturation level increases with the drive current.

Visibility



Sensitive dependence of simultaneous injection locking on frequency matching

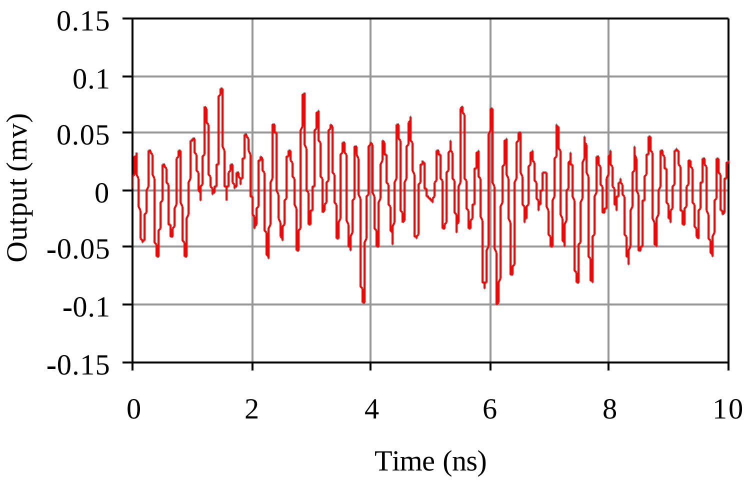
Injection Locking Range



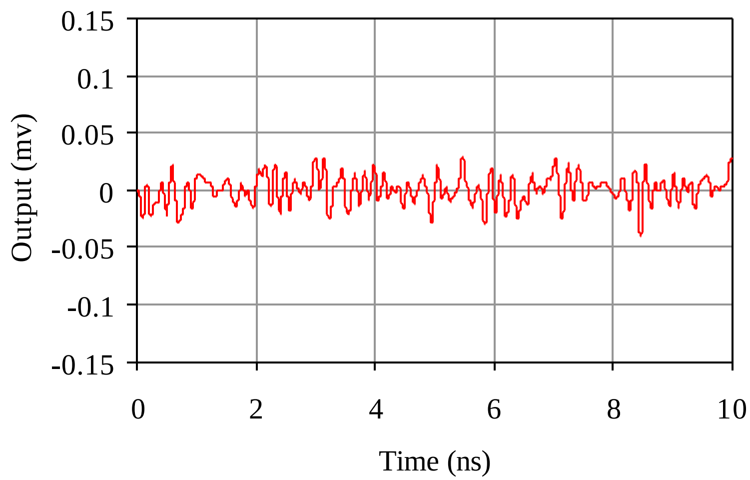
- Stable Locking Range
- At Low Drive Current, the Frequency Range for Stable Locking is Linear with the Injection Strength

Intensity Fluctuations

Multimode

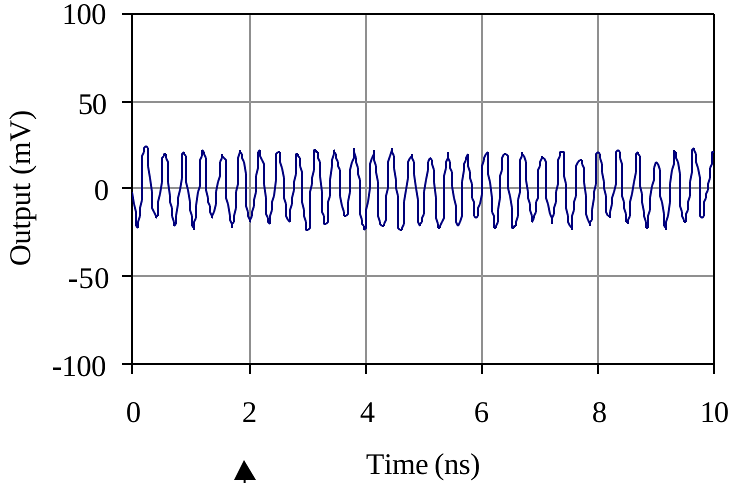


Single Mode



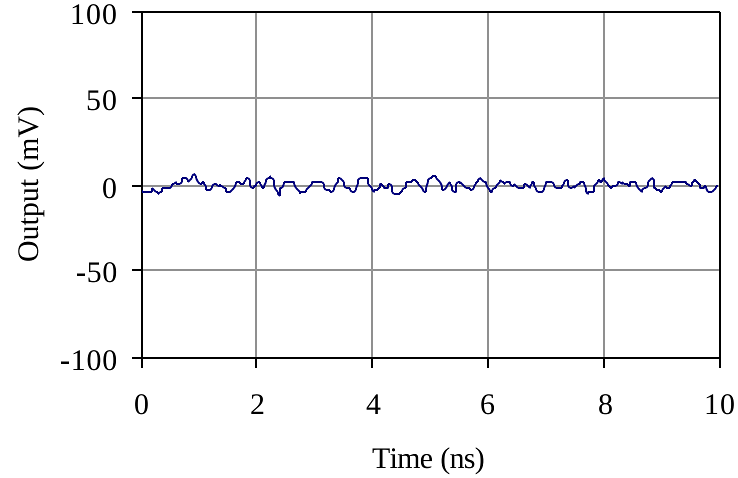
Temporal Dynamics

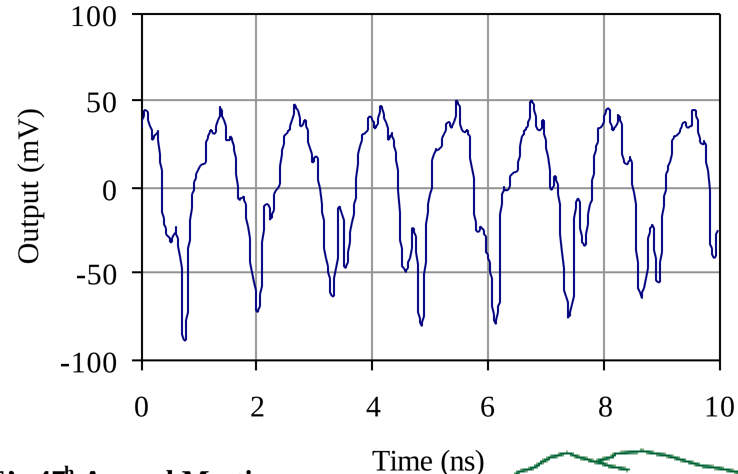
Free-running state



Relaxation oscillations (~3GHz)

Injection-locked states





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

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Y. Liu, H. K. Liu, and Y. Braiman, Proceedings of SPIE's 47th Annual Meeting, Seattle, WA, 2002.

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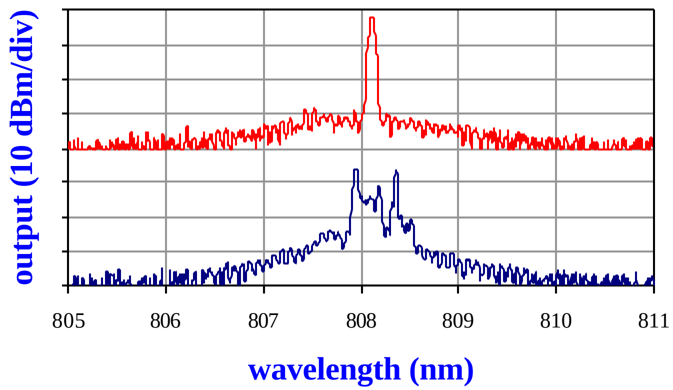
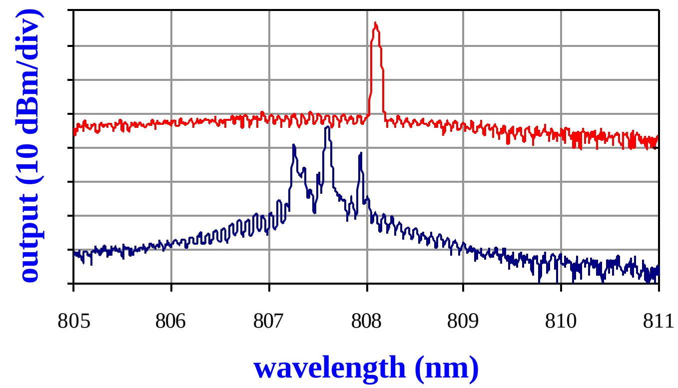
Simultaneous Injection Locking of Two Lasers



LD#7



LD#12

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

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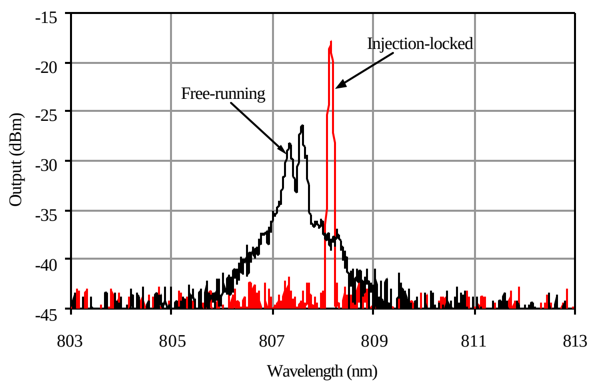
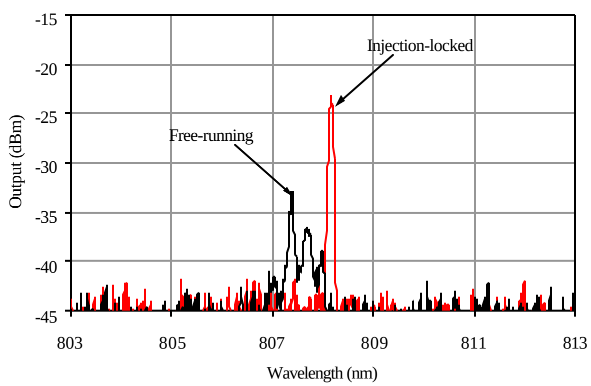
Synchronization of Two Broad-Area Laser Diodes

Optical Spectrum

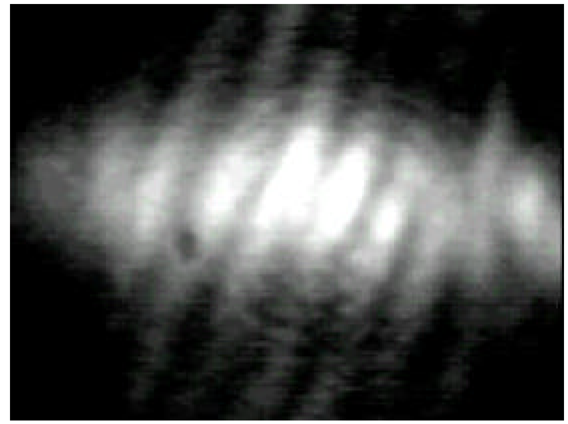


LD #7

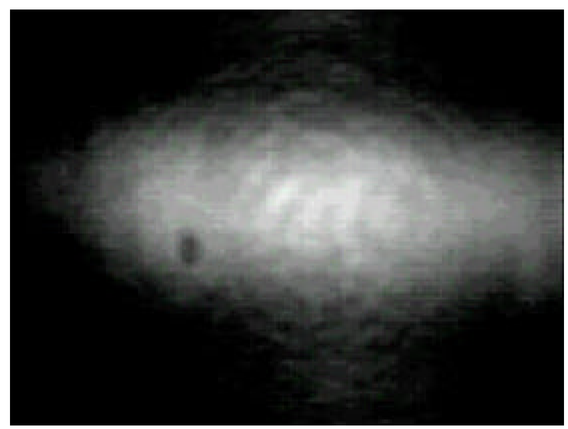


LD #4

Interference Pattern



After Synchronization



Before Synchronization

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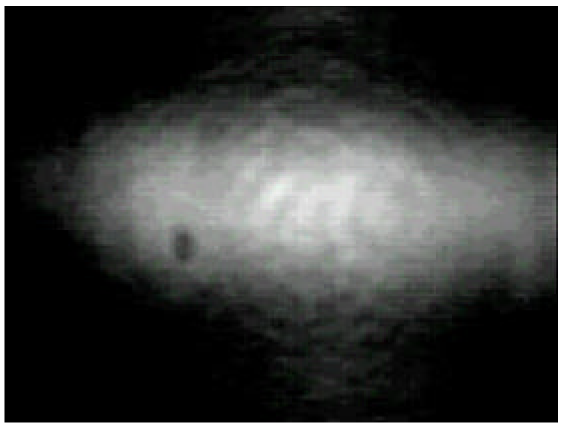
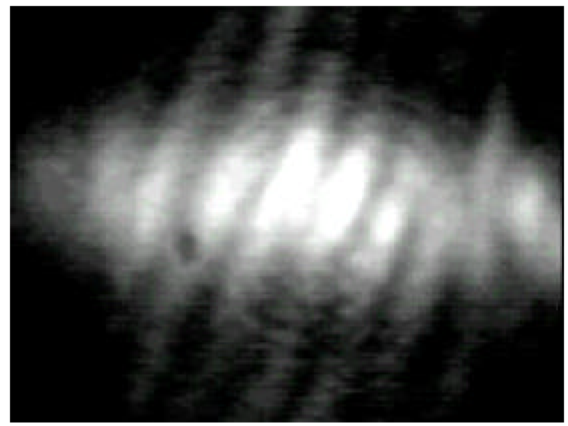
Interference Picture of Injection-Locked Lasers

Stable Phase Relationship Between Lasers
Locking of Transverse Modes



Before Injection Locking



After Injection Locking

Y. Liu, H. K. Liu, and Y. Braiman, Appl. Optics 41, 5036 (2002)

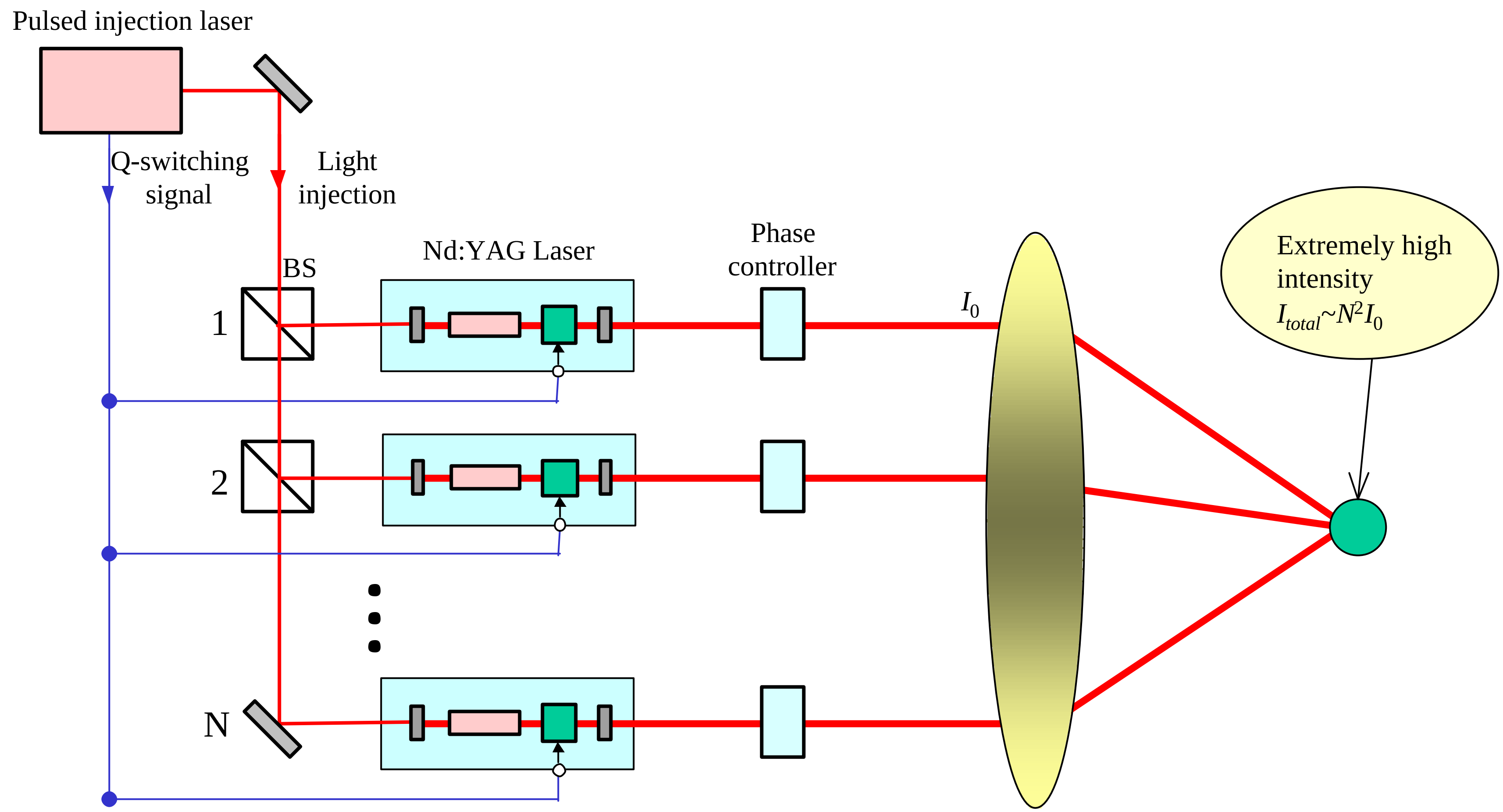
Scalability

We believe our technique can be exploited to achieve synchronization of larger arrays as well as of other several types of class B laser arrays such as semiconductor, solid state, and fiber lasers.

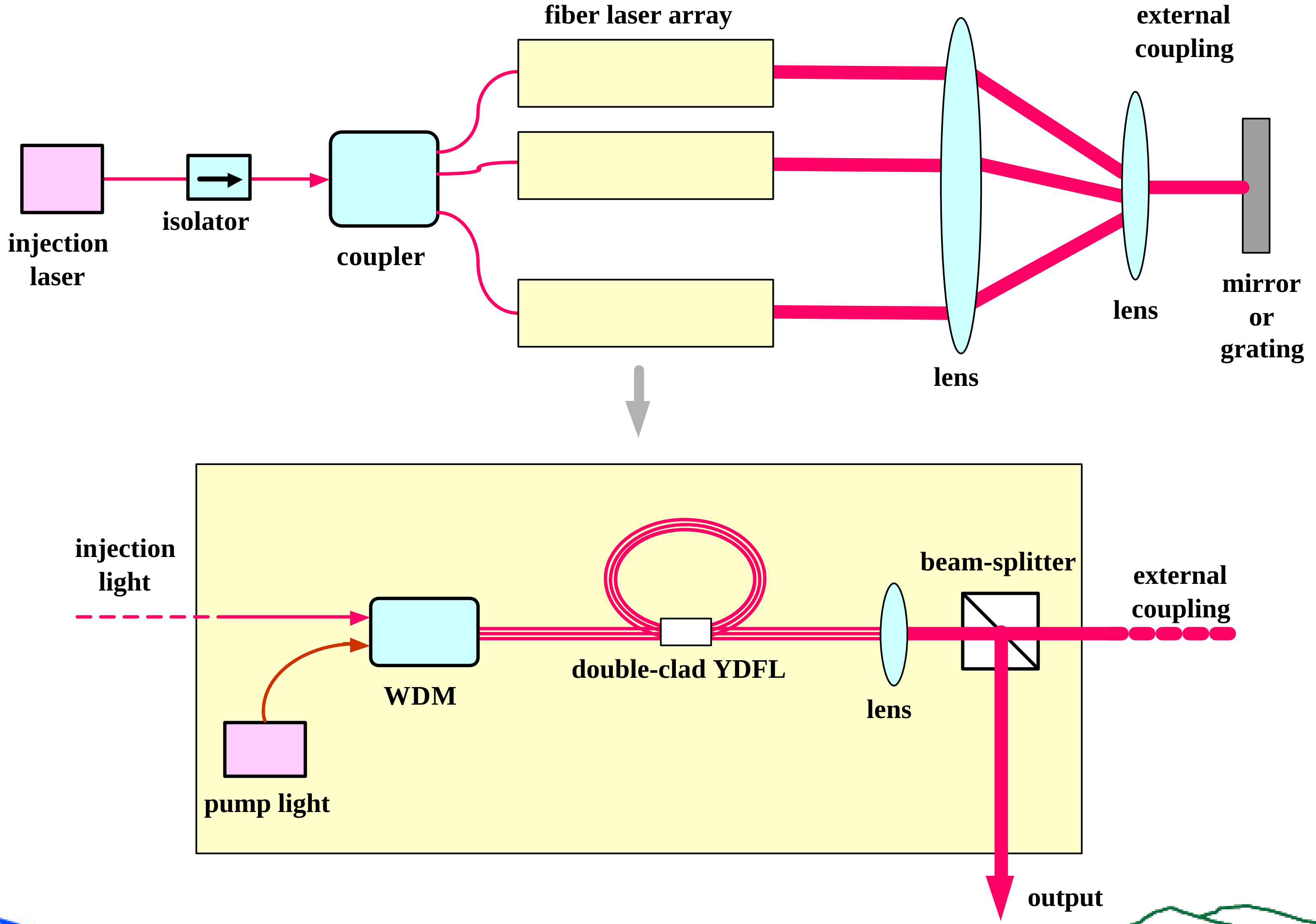
Rationale

- both NdYAG and fiber lasers are considered class B lasers, and are described in very similar ways.
- experimental results readily available for injection locking and synchronization of coupled lasers clearly indicate a large degree of qualitative similarity in behaviors.
- our technique is of a very general and scalable nature: we treat lasers as separate units
  - coupled only through an external cavity to induce collective behavior
  - injection locked to ensure single mode lasing.

Synchronized Nd:YAG Laser Array



Scheme of Coherent Beam Coupling of Fiber Laser Array



Theoretical/Computational Support

- **Simulate the dynamics of the array using the parameters of the experimental setup**
- **Calculate the stability regions of the phase-locked solutions**
- **Use control of chaos techniques to stabilize dynamics of array, if necessary**
- **Combine experimental measurements with numerical predictions using advanced nonlinear uncertainty analysis methods**
  - **best estimates for parameters & reduced uncertainties**

The outstanding benefits: significantly expands the limits of parameter search to synchronize the dynamics of the array and to control chaos.

Rate Equations of Motion for Solid State Laser Array

$$\frac{dE_j}{dt} = [G_j - a_j + id_j)E_j + k(E_{j+1} + E_{j-1}) + E_e$$

$$\frac{dG_j}{dt} = \frac{t_c}{t_f}[p_j - (1 + |E_j|^2)G_j]$$

Electric field in the *j*th laser: $E_j(t)\exp(-i?_0 t)$

G_j	the gain
t_f	fluorescence time (~240μs)
t_s	cavity round trip time (~ 2ns)
p	pumping rate
κ	magnitude of the coupling strength between adjacent lasers
δ_j	detunings
a	losses

Equations of Motion

Substitute

$$E_e(t) = \sqrt{I_e}$$
$$E_j(t) = \sqrt{I_j}(t)\exp(i f_j(t))$$

To obtain

$$\dot{I}_j = 2(G_j - a)I_j + 2k\sqrt{I_1 I_2}\cos(f_2 - f_1) + 2\sqrt{I_e I_j}\cos f_j$$

$$\dot{f}_j = d_j + (-1)^j k\frac{\sqrt{I_1 I_2}}{I_j}\sin(f_1 - f_2) - \sqrt{\frac{I_e}{I_j}}\sin f_j$$

$$\dot{G}_j = \frac{t_c}{t_f}(p - G_j - G_j I_j)$$

Stability Analysis of the Phase Model

$$\dot{f}_j = d_j - |k|\{\sin(f_{j+1} - f_j) + \sin(f_{j-1} - f_j)\} - A_e \sin f_j$$

$$d_j = 0 \Rightarrow f_j^0 = 0 \quad \text{is a solution}$$

Stability ?

$$f_j(t) = f_j^0 + df_j(t)$$

$$d\dot{f}_j = -|k|[df_{j+1} - 2df_j + df_{j-1}] - A_e df_j$$

$$df_j = x_{jm} \exp(l_m t) \qquad \Rightarrow l_m = -A_e + 4|k|\sin^2 \frac{mp}{N}, \quad m = 0,1,\ldots N-1$$

In-phase solution stable for $\boxed{A_e > 4|k|}$

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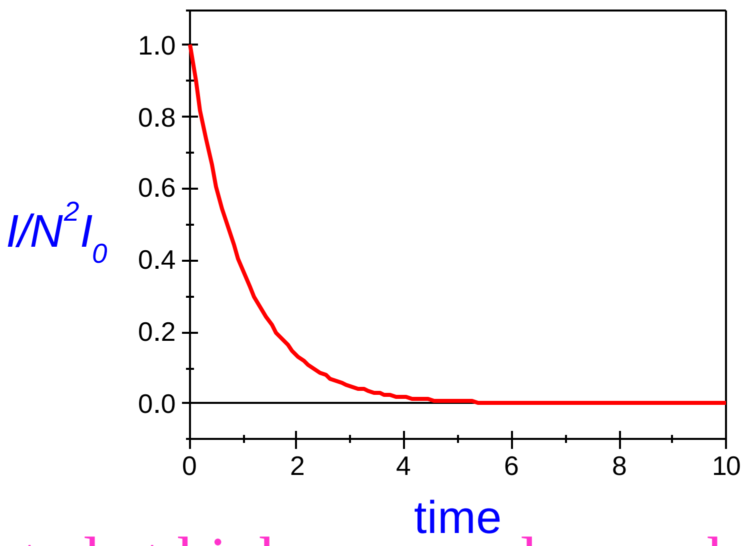
Y. Braiman, A. I. Khibnik, T. A. B. Kennedy, and K. Wiesenfeld, Phys. Rev. A 52, 1500 (1995);

Stability of the "In-phase" Solution

* In-phase solution is not stable for a wide range of parameters.

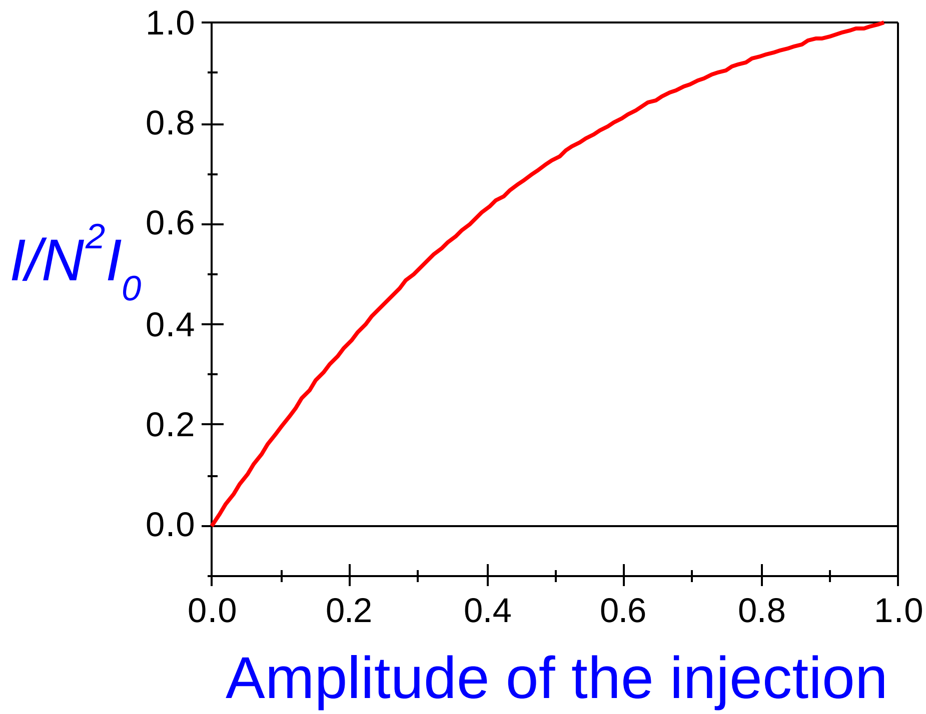
* Instead, the "Out-of-phase" solution ($\phi_{j+1} - \phi_j = \pi$) is stable, leading to a destructive interference.



* When operated at high power - lasers show chaotic behavior.

Entrainment by Injection of the Field

Injection of the same electromagnetic field in to the cavity of each laser results in stabilization of the "in-phase behavior".



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Two Coupled Lasers

$$\dot{f}_1 = d_1 + k(\sin(f_1 - f_2)) - A_e \sin f_1$$

$$\dot{f}_2 = d_2 + k(\sin(f_2 - f_1)) - A_e \sin f_2$$

Fixed Point Solutions

$$d_1 + k(\sin(f_1 - f_2)) - A_e \sin f_1 = 0$$

$$d_2 + k(\sin(f_2 - f_1)) - A_e \sin f_2 = 0$$

Injection Tuning

$$d_1 + d_2 \simeq 0$$

Analysis of the Phase Model

$$\sin f_1 + \sin f_2 = 0$$

$$d_1 - d_2 + 2k(\sin(f_2 - f_1)) - A_e(\sin f_2 - \sin f_1) = 0$$

The first equation in (1.3) implies that either a): $f_2 - f_1 = (2m+1)p$ or

b): $f_1 + f_2 = 2pm$, where m is an integer. Solutions of class (a) imply $\sin(f_2 - f_1) = 0$, yielding $\sin f_1 = d_1 / A_e$, $\sin f_2 = d_2 / A_e$ and $\sin(f_1 - f_2) = \sin(\sin^{-1}(d_1/A_e) - \sin^{-1}(d_2/A_e)) \neq 0$, i.e. inconsistency. Hence, the only possibility is the class (b) of solutions which, in turn, can be divided in two sub-classes: m even and m odd. For m even, the second equation in becomes:

$$f(x) \equiv -d - 2k \sin x - 2A_e \sin\frac{x}{2} = 0$$

Nonmonotonicity Transition Point

$$f(x) = -d - 2k \sin x_c - A_c \sin \frac{x_c}{2} = 0$$

$$f'(x) = -2k \cos x_c - A_c \cos \frac{x_c}{2} = 0$$

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

$$\tan x_c / 2 = z$$

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

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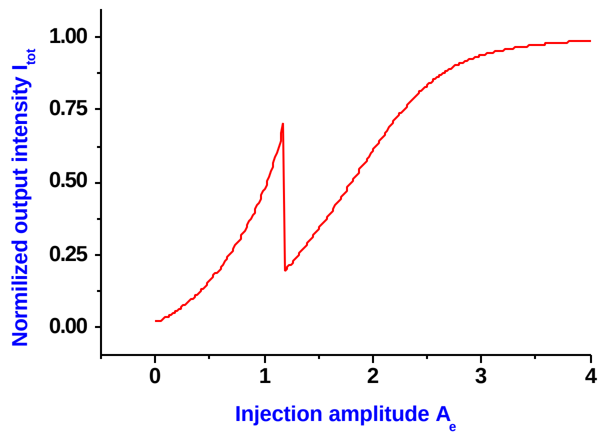
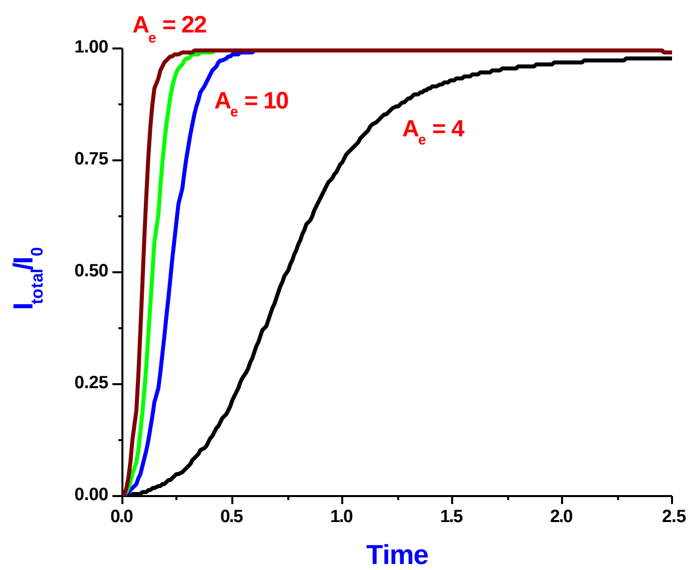
Theoretical/Computational Research

Entrainment of the Array and Control of Transient Times

The total output intensity may not grow monotonically with the injection strength.





At $A_c = -2k\,\dfrac{1 - z^2}{\sqrt{1 + z^2}}$ **the intensity drops.**

$z = (-q/2 + \sqrt{D})^{1/3} + (-q/2 - \sqrt{D})^{1/3}$

$D = (p/3)^3 + (q/2)^2$

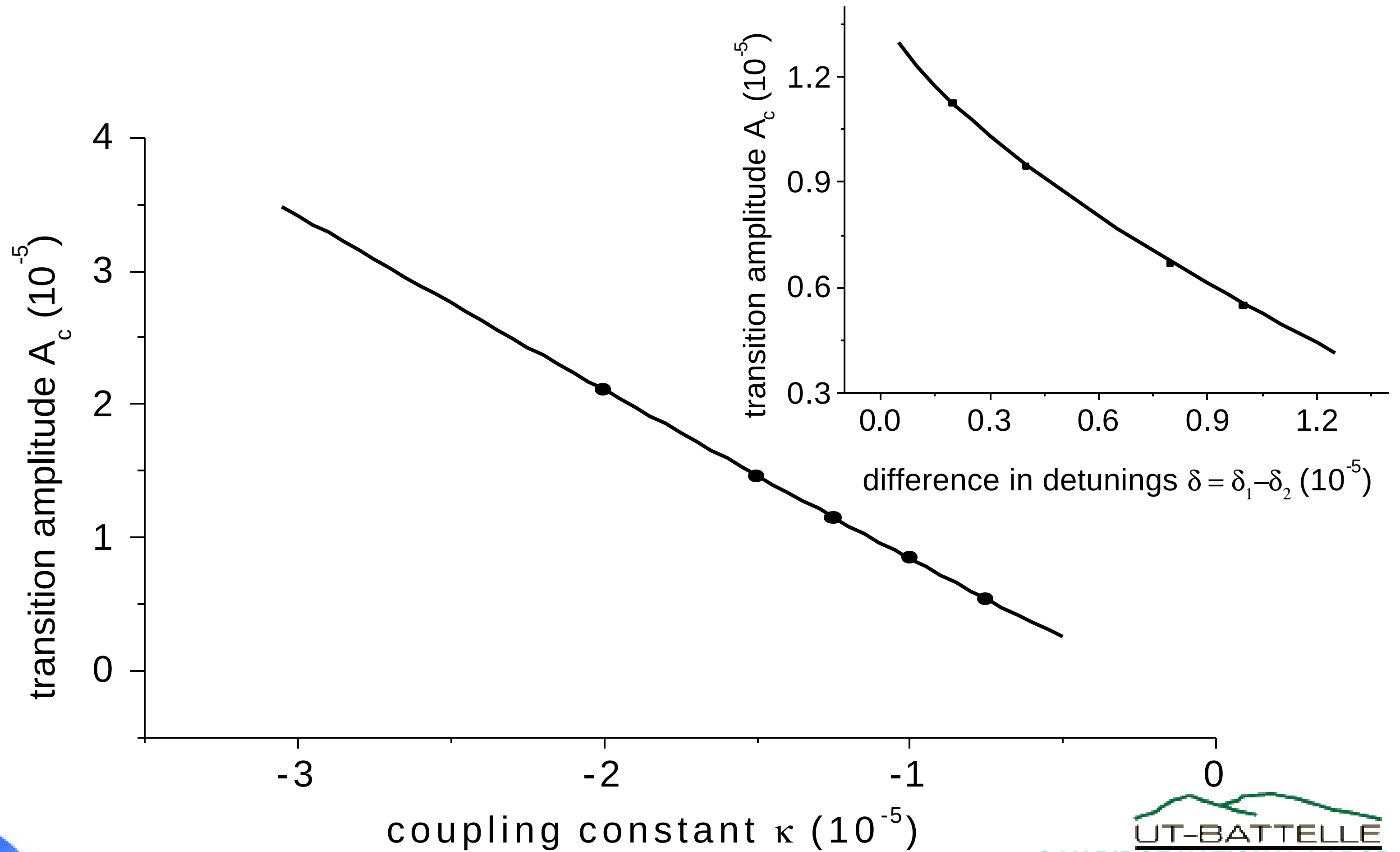
$^2/48k^2$ and $q = d/4k + d^3/864k^3$

k **is the coupling constant**

Transient times from the out-of-phase (minimum intensity) to the in-phase (maximum intensity) can be achieved by controlling the injection field.

A. I. Khibnik, Y. Braiman, V. Protopopescu, T. A. B. Kennedy, and K. Wiesenfeld, Phys. Rev. A 62, 063815 (2000); E. Jung, S. Lenhart, V. Protopopescu, and Y. Braiman, submitted to Phys. Rev. Lett. (2002).

Comparison of the Analysis with Numerical Simulations



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Equation of Motion for Semiconductor\ Laser Array

$$\frac{dE_j}{dt} = [G_j - a_j + id_j)E_j + k(E_{j+1} + E_{j-1}) + E_e$$

$$\frac{dG_j}{dt} = \frac{t_c}{t_f}[p_j - (1 + |E_j|^2)G_j]$$

Electric field in the *j*th laser: $E_j(t)\exp(-i?_0 t)$

G_j	the gain
t_f	fluorescence time (~240µs)
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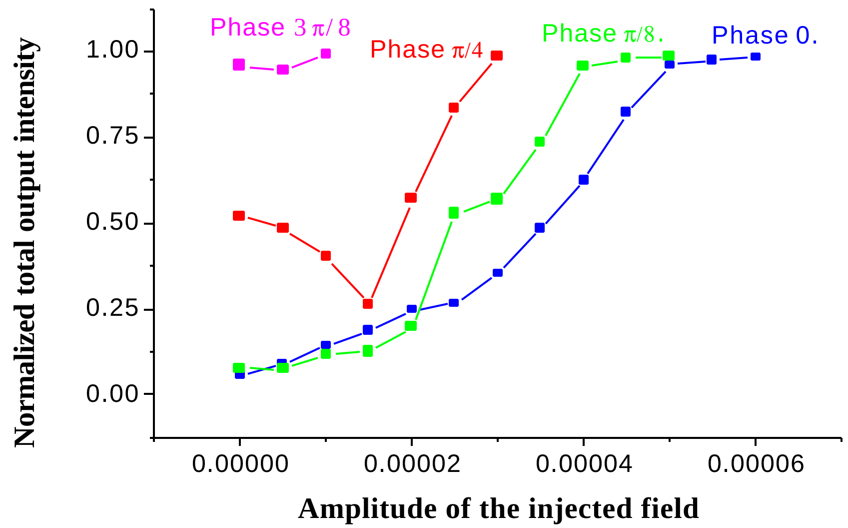
p	pumping rate
κ	magnitude of the coupling strength between adjacent lasers
δ_j	detunings
a	losses

External Cavity Coupling

Dynamics and Synchronization of a Nonlinear Array of Coupled Oscillators

Additional Challenges:

- **Chaos**
- **Time Delay**
- **Discrete (non-continuum)**



$$\dot{E}_j(t) = (1 - ia)Z_j(t)E_j(t) + k_j E_j(t - t)e^{-if_j} + k_{ext}E_{ext}(t)$$

$$+ k_{j+1}E_{j+1}(t - t)e^{-if_j} + k_{j-1}E_{j-1}(t - t)e^{-if_j} + id_j E_j(t)$$

$$\dot{Z}_j(t) = g_R[p_j - Z_j(t) - (2Z_j(t) + 1)|E_j(t)|^2]$$

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Summary

- **Proposed an experimental setup to injection-lock a broad-area laser diode array.**

- **Systematically investigated conditions for injection locking of broad-area lasers.**

- **Simultaneous injection of two broad-area lasers in a 19-laser array.**

- **Our experiments suggest the feasibility of achieving high intensity diffraction limited coherent radiation from an array of broad-area lasers.**

Summary

- **Light source for space optical communication**
  - **Synchronizing and coherent beam coupling of high-power 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.**

Problems

Array inhomogeneity
Limited injection power

Future work

Separate control of individual laser
Cascaded injection scheme

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