Coherence and Synchronization in Arrays Lasers

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Motivation

Ultra High Coherent Power (2-10W)

Ultra Fast (10Gbps) Communication Rates

Desired Properties of Waveform

In-Phase Synchronization

Attractor Switching

Control of Spatial and Temporal Dynamics

Laser Array as a Dynamical System

- In -phase synchronization in a single array
- Chaotic synchronization of distinct laser arrays
- Suppression of chaos in laser arrays
- Control of transient behaviors
- Fast attractor switching

Synchronization

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

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

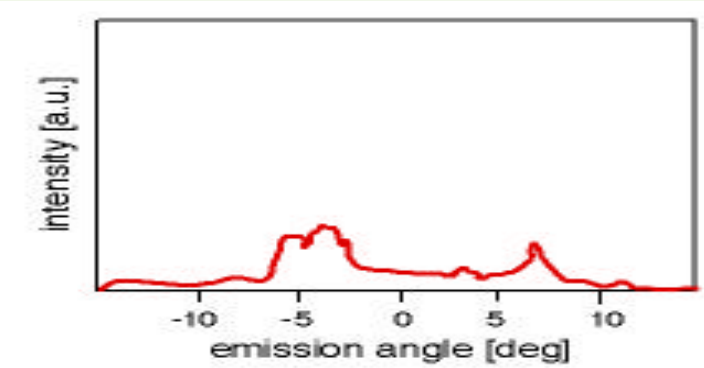
E_j - complex amplitude

ω_j - the frequency

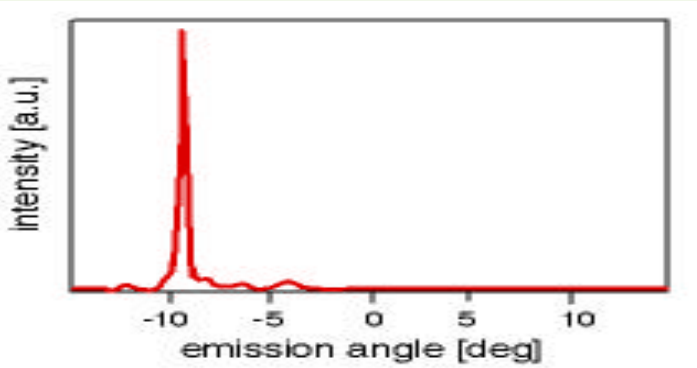
$$E_j = \sqrt{I_j}\, e^{i\phi_j}$$

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

$\Rightarrow I \sim N^2 I_0$

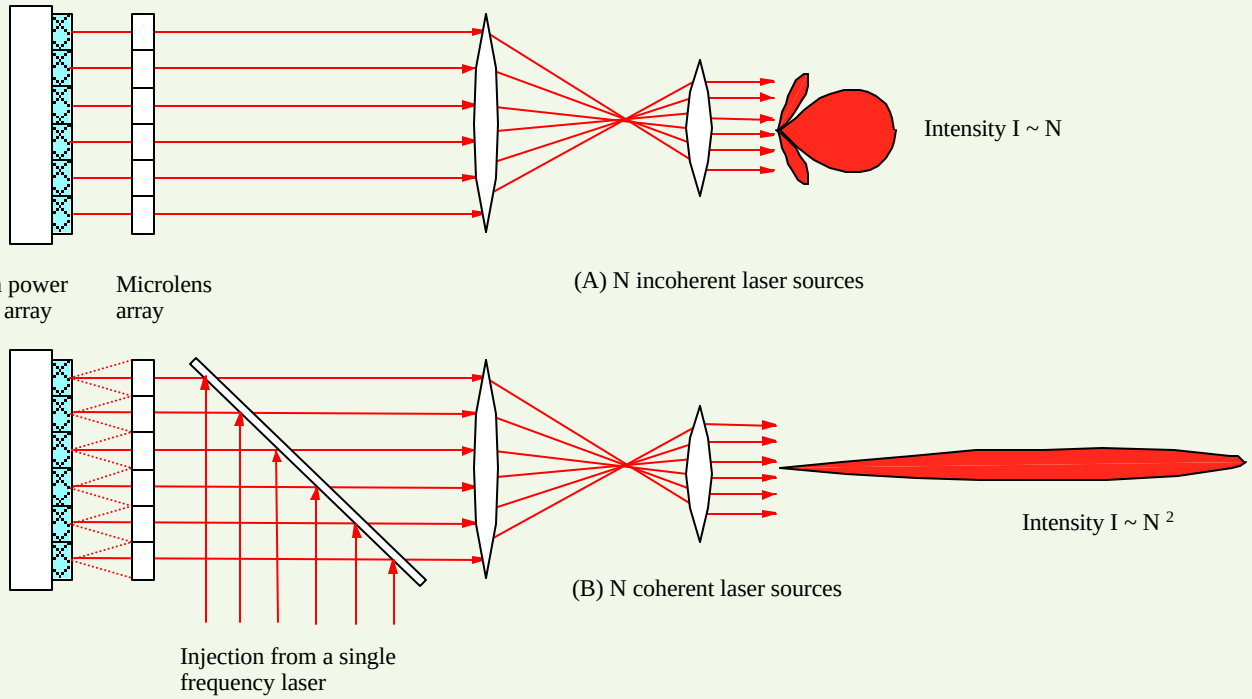


Noncoherent addition



Coherent addition

High Coherent Power Generation Using Arrays of Semiconductor Lasers



Attributes/Benefits of this Concept

- Compact high intensity power source
- Potential of order of magnitude increase in power
- Cost effective - semiconductor lasers are not expensive

Additional (Potential) Applications

- High Speed Image Transmission (in Gbps rate)
- Improved Space Communications
  (more power, larger distances)
- Pumping Solid State Lasers

Why has high coherent power not yet been achieved in lasers ?

Array Synchronization & Stability

- In-phase behavior of identical lasers is not stable for a broad range of parameters
- High power arrays are not stable

- Optics + Lasers + Nonlinear Dynamics & Chaos

- Nontrivial Combination !

What has already been achieved ?

- Phase locking by injection of a single laser
- Synchronization of low power nonchaotic arrays of lasers
- Synchronization of two - three chaotic lasers

Basic Equations for Semiconductor Laser Array

Evolution of mode amplitude E_j and population N_j in the jth laser

$$\frac{dE_j}{dt} = \frac{1}{2}[G(N_j) - \frac{1}{\tau_p}](1 - i\alpha)E_j + i\kappa(E_{j+1} + E_{j-1}) + i\delta_j E_j + E_e$$

$$\frac{dN_j}{dt} = p - \frac{N_j}{\tau_s} - G(N_j)\,|E_j|^2$$

Electric field in the jth laser: $E_j(t)\exp(-i\omega_0 t)$

N_j	inversion population
G_j	gain
τ_p	photon lifetime (~1 ps)
τ_s	lifetime of the active population (~ 2ns)
p	pumping rate
κ	magnitude of the coupling strength between adjacent lasers
δ_j	uncoupled laser frequencies
α	line-width enhancement factor

$$G(N_j) = G(N_{th}) + g(N_j - N_{th})$$

$g = \partial G/\partial N$ - the differential gain and $G(N_{th}) = 1/\tau_p$

Equation of Motion for Semiconductor Laser Array

$$\frac{dE_j}{dt} = [G_j - \alpha_j + i\delta_j)E_j + \kappa(E_{j+1} + E_{j-1}) + E_e$$

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

Electric field in the *j*th laser: $E_j(t)\exp(-i\omega_0 t)$

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

Equations of Motion

Substitute

$$E_e(t) = \sqrt{I_e}$$

$$E_j(t) = \sqrt{I_j}(t)\exp(i\phi_j(t))$$

To obtain

$$\dot{I}_j = 2(G_j - \alpha)I_j + 2\kappa\sqrt{I_1 I_2}\cos(\phi_2 - \phi_1) + 2\sqrt{I_e I_j}\cos\phi_j$$

$$\dot{\phi}_j = \delta_j + (-1)^j \kappa \frac{\sqrt{I_1 I_2}}{I_j}\sin(\phi_1 - \phi_2) - \sqrt{\frac{I_e}{I_j}}\sin\phi_j$$

$$\dot{G}_j = \frac{\tau_c}{\tau_f}(p - G_j - G_j I_j)$$

Stability Analysis of the Phase Model

$$\dot{\phi}_j = \delta_j - |\kappa|\{\sin(\phi_{j+1} - \phi_j) + \sin(\phi_{j-1} - \phi_j)\} - A_e \sin\phi_j$$

$$\delta_j = 0 \Rightarrow \phi_j^0 = 0 \quad \text{is a solution}$$

Stability ?

$$\phi_j(t) = \phi_j^0 + \delta\phi_j(t)$$

$$\delta\dot{\phi}_j = -|\kappa|[\delta\phi_{j+1} - 2\delta\phi_j + \delta\phi_{j-1}] - A_e\delta\phi_j$$

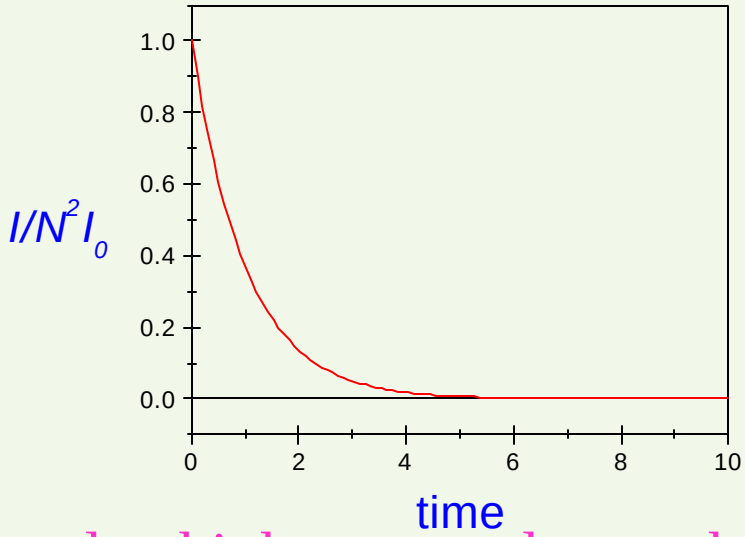
$$\delta\phi_j = x_{j\mu}\exp(\lambda_\mu t) \qquad \Rightarrow \lambda_\mu = -A_e + 4|\kappa|\sin^2\frac{\mu\pi}{N}, \quad \mu = 0,1,\ldots N-1$$

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

Stability of the "In-phase" Solution

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

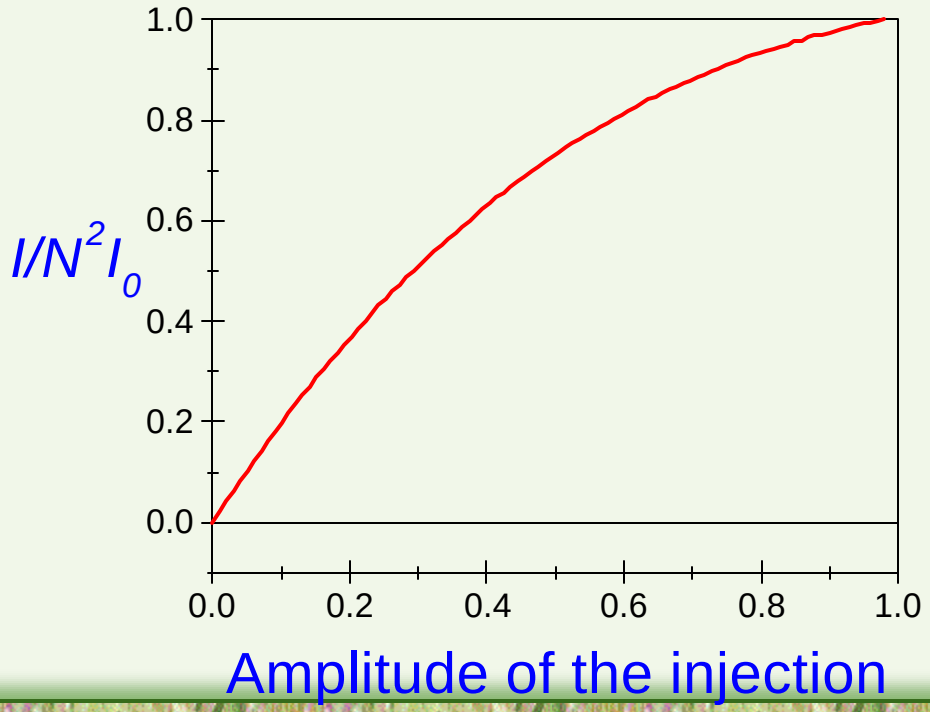
* Instead, the "Out-of-phase" solution ($\phi_{j+1} - \phi_j = \pi$) is stable, leading to a destructive interference.



* 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”.



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

$$\delta_1 + \delta_2 \simeq 0$$

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 in (1.3) implies that either a): $\phi_2 - \phi_1 = (2m+1)\pi$ or b): $\phi_1 + \phi_2 = 2\pi m$, where m is an integer. Solutions of class (a) imply $\sin(\phi_2 - \phi_1) = 0$, yielding $\sin\phi_1 = \delta_1 / A_e$, $\sin\phi_2 = \delta_2 / A_e$ and $\sin(\phi_1 - \phi_2) = \sin(\sin^{-1}(\delta_1 / A_e) - \sin^{-1}(\delta_2 / A_e)) \neq 0$, 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:

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

Nonmonotonicity Transition Point

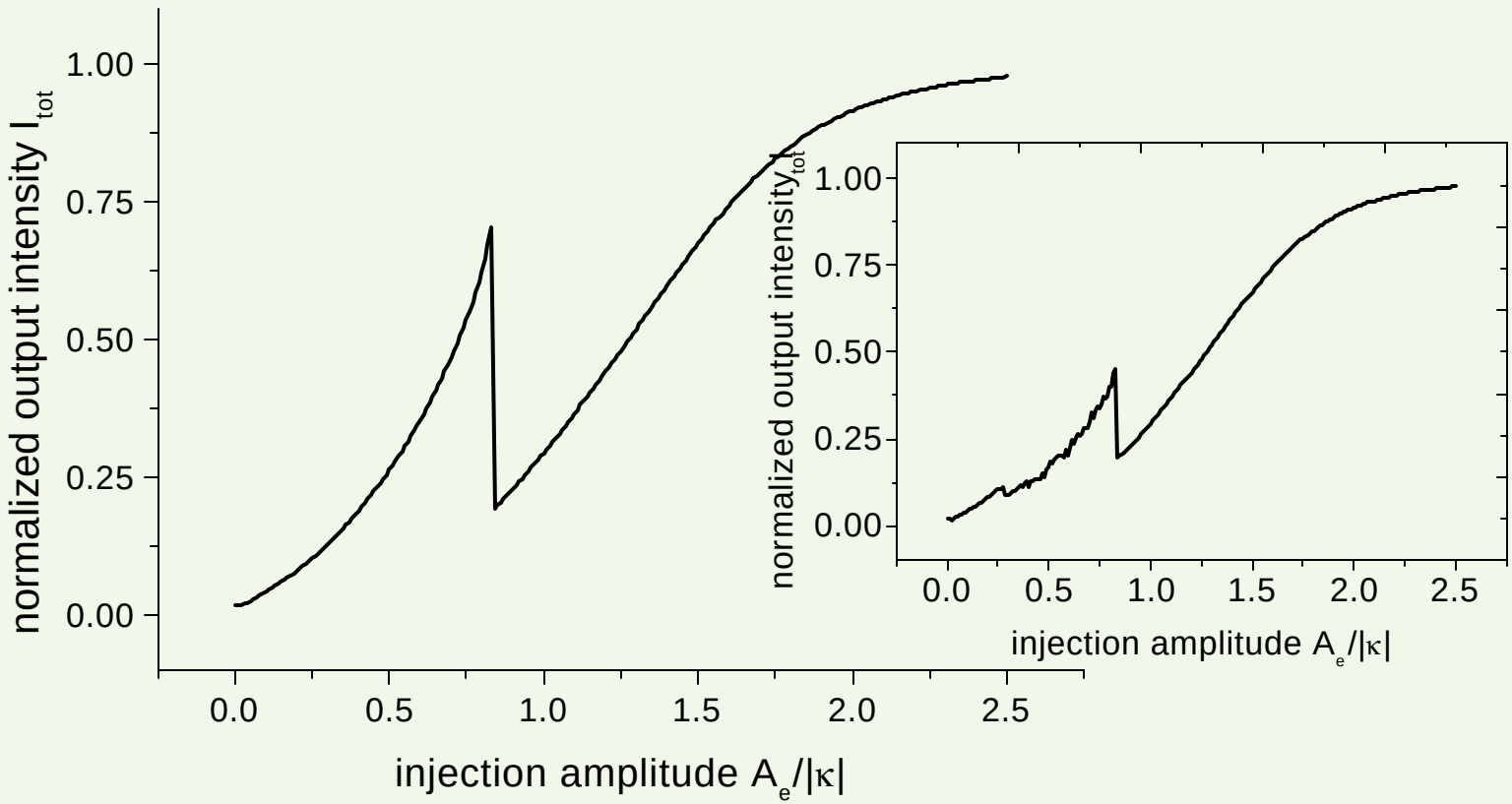
$$f(x) = -\delta - 2\kappa \sin x_c - A_c \sin \frac{x_c}{2} = 0$$

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

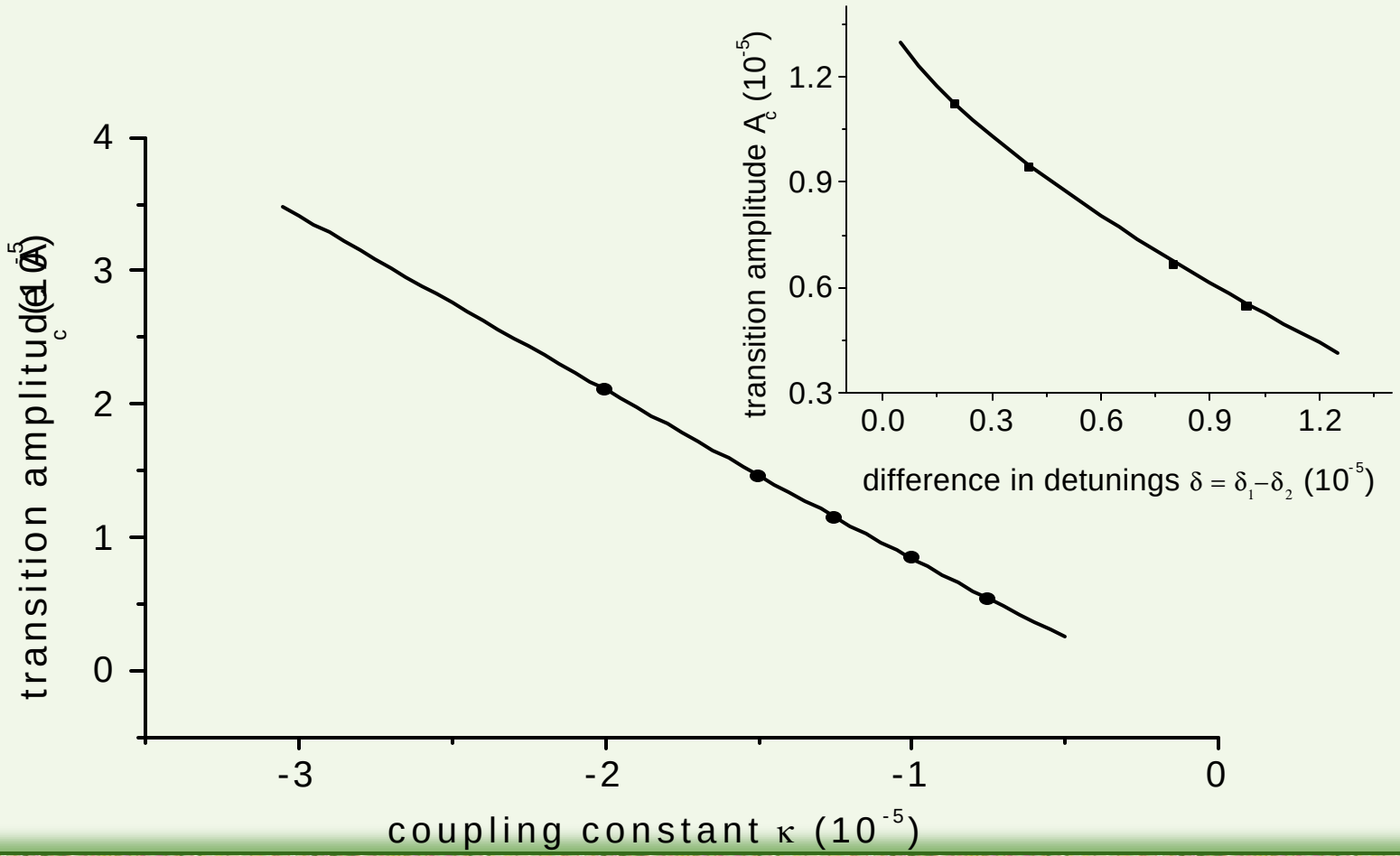
$$A_c = -2\kappa \frac{1 - z^2}{\sqrt{1 + z^2}}.$$

$$\tan x_c / 2 = z$$

Nonmonotonicity



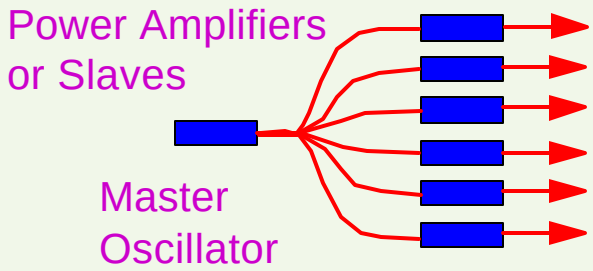
Comparison of the Analysis with Numerical Simulations



Commonly Used Array Architectures

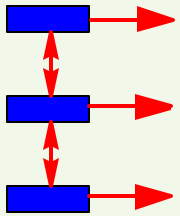
MOPA/Injection Locking

Single, stable mode from master oscillator

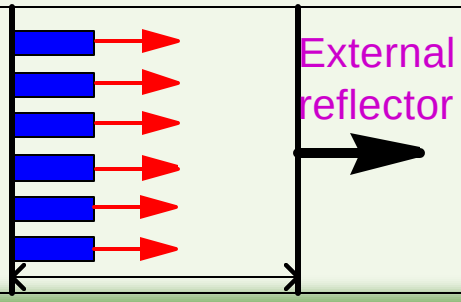


Coupled Oscillators

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



External Cavities



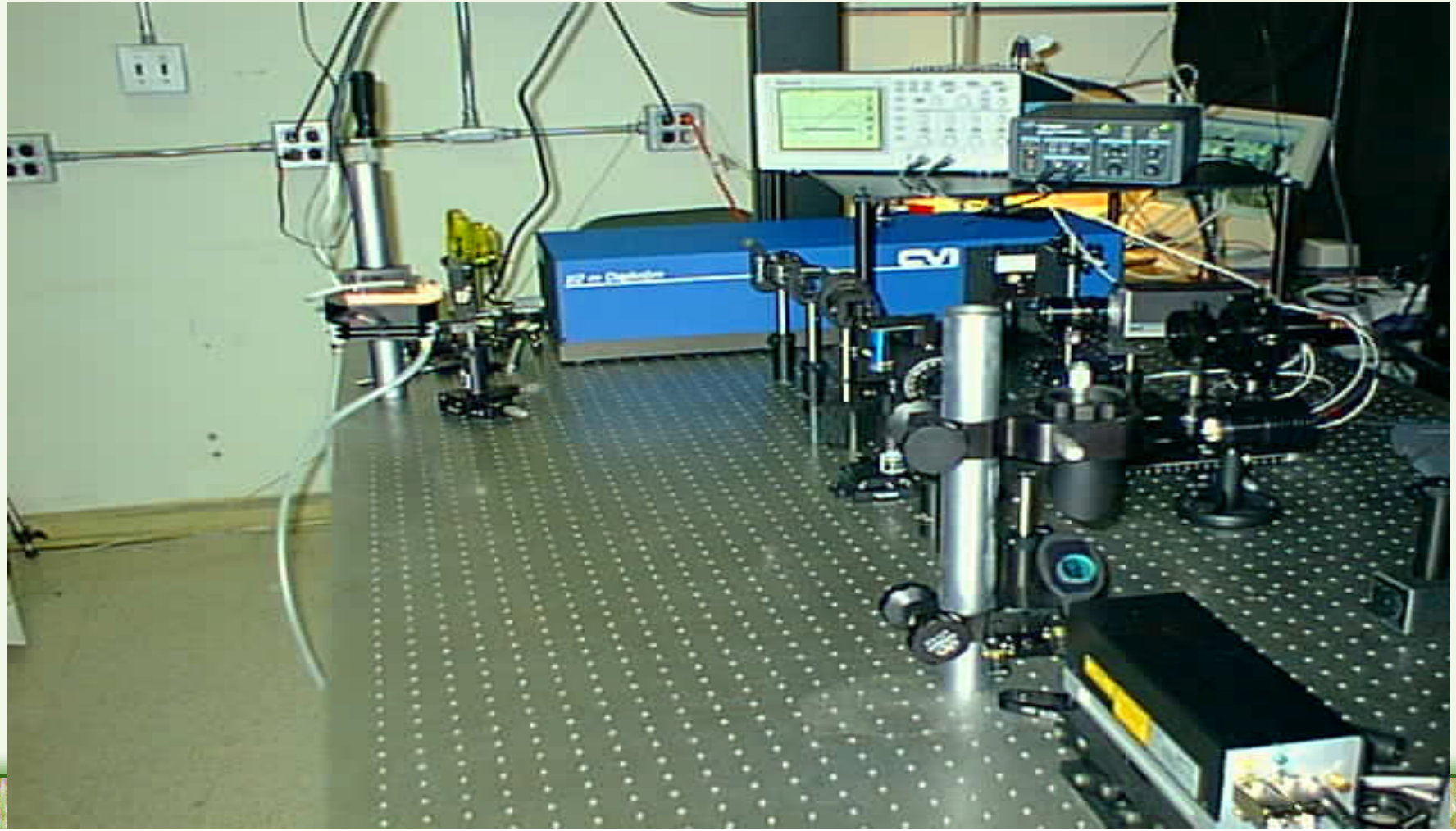
Challenges

- Beam injection into each laser
  - achieve distribution controlled injection under micro-optic geometrical constraints
- Phase locking the array
  - 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

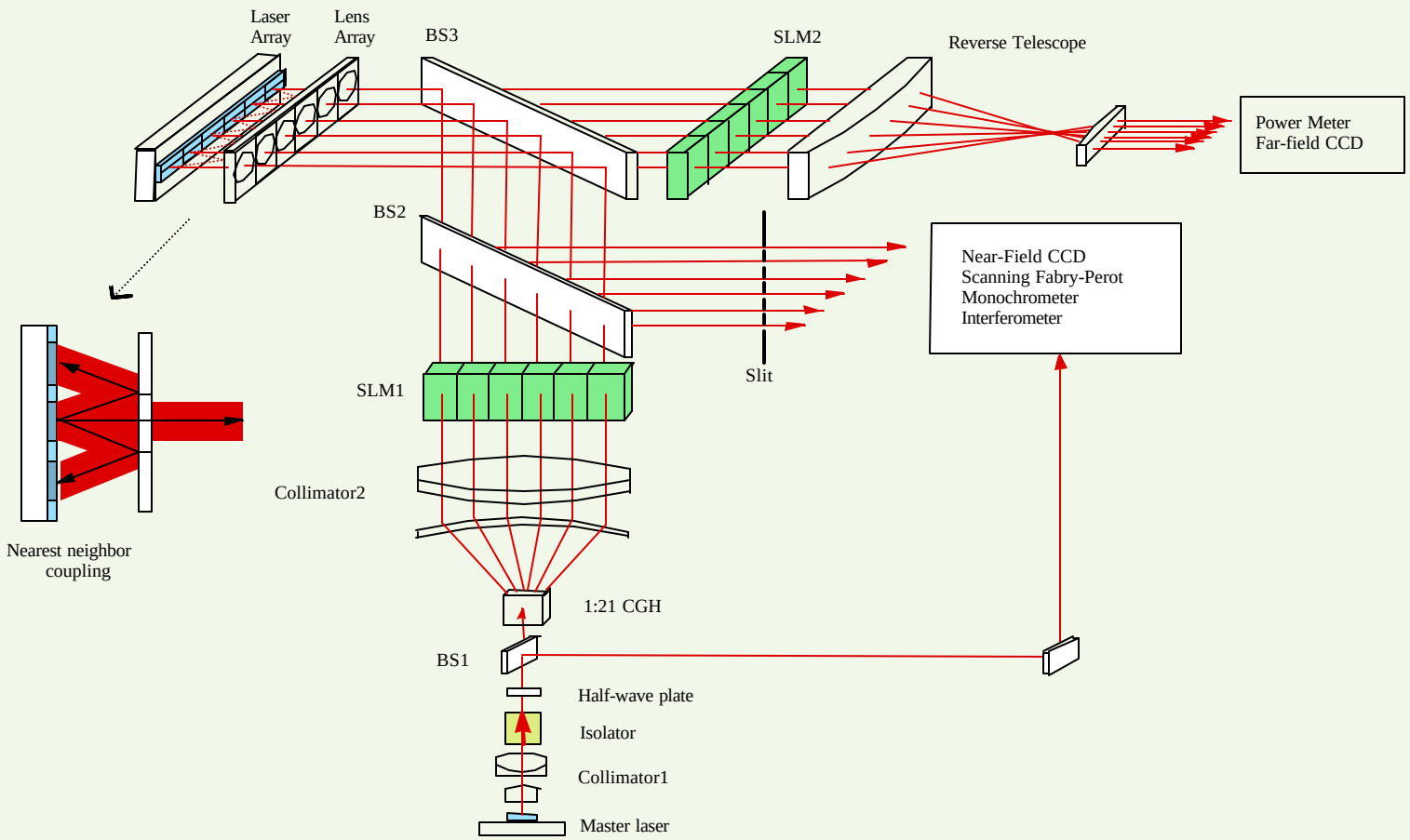
Approach

- Control output power of array by changing the amplitude and the frequency of the injected field
- Modulate injected field to produce a high power modulated output field
- Achieve coupling by feedback from neighboring lasers
  - enables us to control coupling strength
- Our starting point is an uncoupled array
  - λ = 810 nm d = *500 micron*
  - Because of *large* separation between array elements, we can control injection

Experimental Apparatus

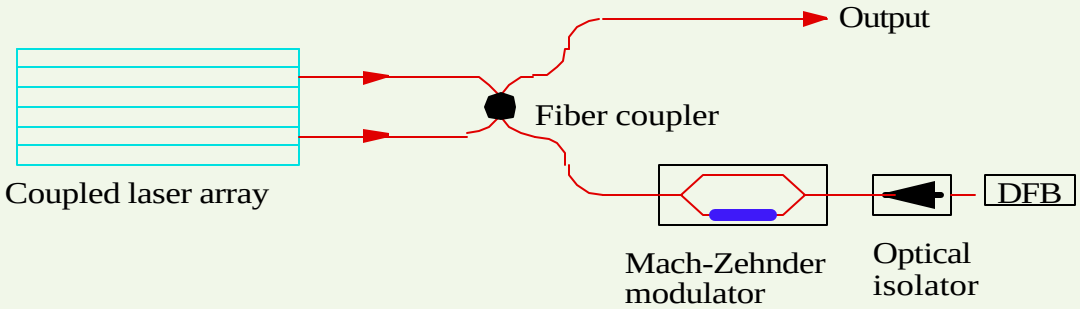


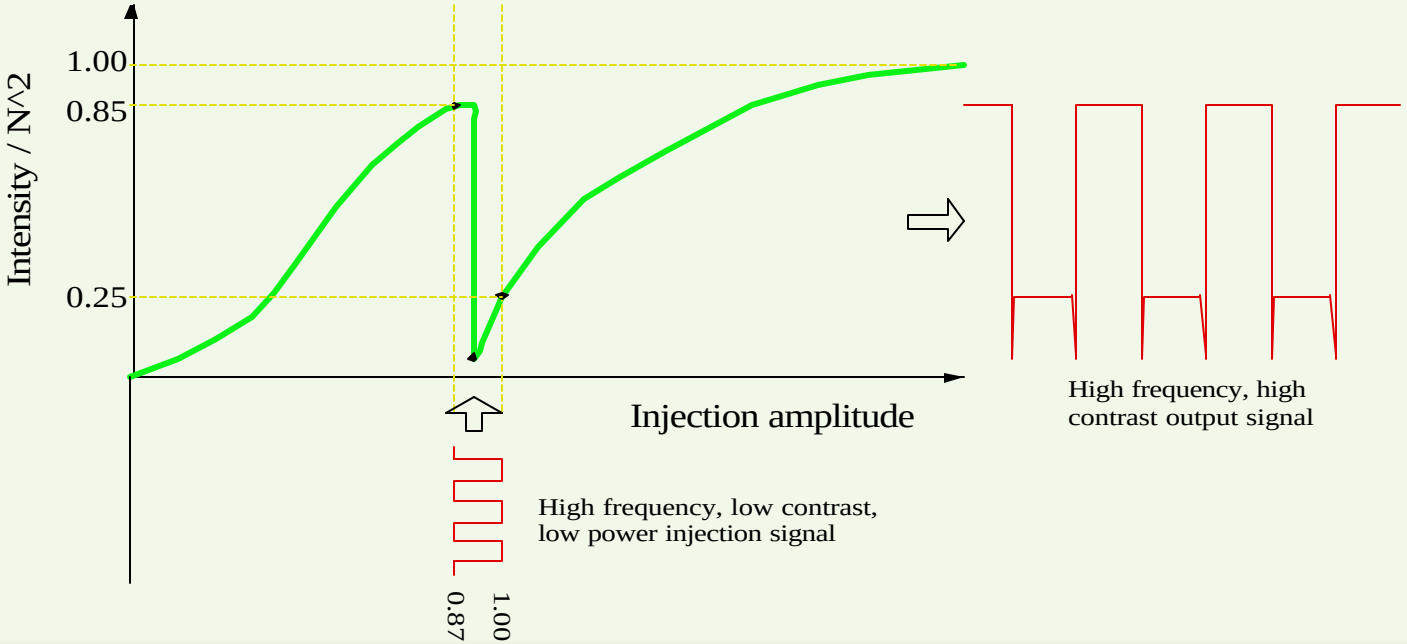
Schematic Diagram of Experiment



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

High Contrast Fast Modulation (Gbps)





Proposed Design

- control the injection amplitudes and phase distribution ***to each laser separately***
- control the form and the strength of the coupling between lasers
- measure the amplitudes and the phases of ***each laser separately***

Combining Experimental Measurements with Numerical/Theoretical Analysis

a) Computation and analysis of the equations of motion for a specific arrays of lasers.

b) Estimation of the range of parameters where the experimental probability for obtaining high power output radiation from the array is maximized.

Publications

- Y. BRAIMAN, T. A. B. KENNEDY, K. WIESENFELD, and A. I. KHIBNIK, *Entrainment of Solid-State Laser Arrays*, Phys. Rev. A **52**, 1500, (1995).
- A. I. KHIBNIK, Y. BRAIMAN, T. A. B. KENNEDY, and K. WIESENFELD, *Phase Model Analysis of Two Lasers with Injected Field*, Physica D **111**, 295 (1998).
- A. KHIBNIK, Y. BRAIMAN, V. PROTOPOPESCU, T. A. B. KENNEDY, and K. WIESENFELD, *Amplitude Dropout in Coupled Lasers*, submitted to Phys. Rev. A (May, 2000).