Coherence and Synchronization in Arrays of Class B Lasers

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Motivation

Ultra High Coherent Power (2-10W)

In-Phase Synchronization

Ultra Fast (10Gbps) Communication Rates

Attractor Switching

Desired Properties of Waveform

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

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

$$I(t) = |\sqrt{I_1}\exp(if_1) + \sqrt{I_2}\exp(if_2) + ...|^2$$

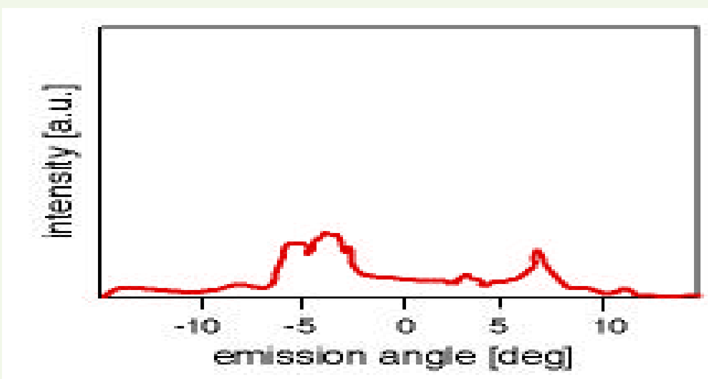
E_j - complex amplitude

ω_j - the frequency

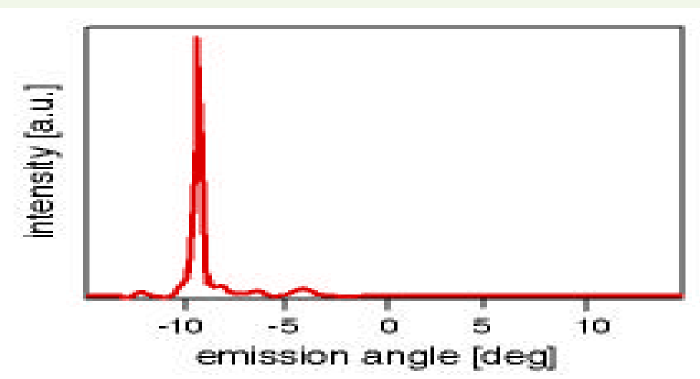
$$E_j = \sqrt{I_j}\, e^{if\, j}$$

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

$\Rightarrow I \sim N^2 I_0$

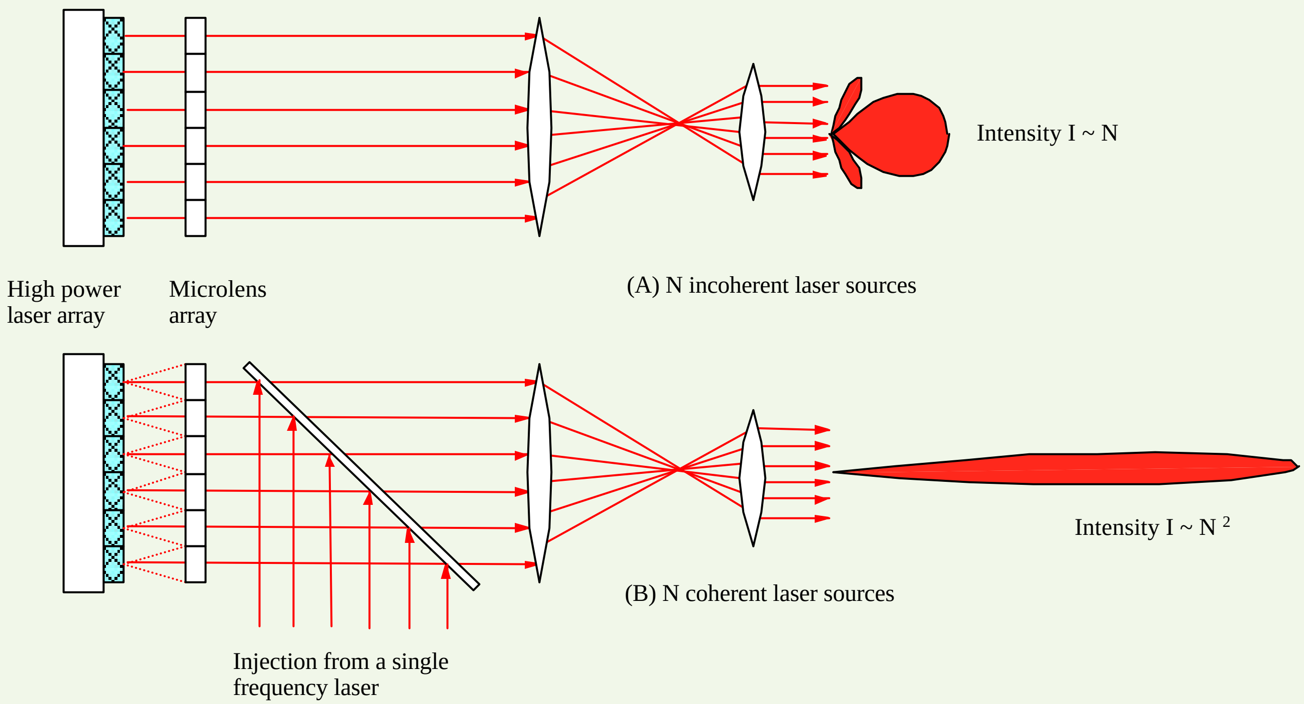


Noncoherent addition



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

$$\frac{dE_j}{dt} = \frac{1}{2}[G(N_j) - \frac{1}{t_p}](1 - ia)E_j + ik(E_{j+1} + E_{j-1}) + id_j E_j + E_e$$

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

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

N_j	inversion population
G_j	gain
t_p	photon lifetime (~1 ps)
t_s	lifetime of the active population (~ 2ns)
p	pumping rate
κ	magnitude of the coupling strength between adjacent lasers
δ_j	uncoupled laser frequencies
a	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

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

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

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

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

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

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

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

$d_j = 0 \Rightarrow f_j^0 = 0$ is a solution

Stability ?

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

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

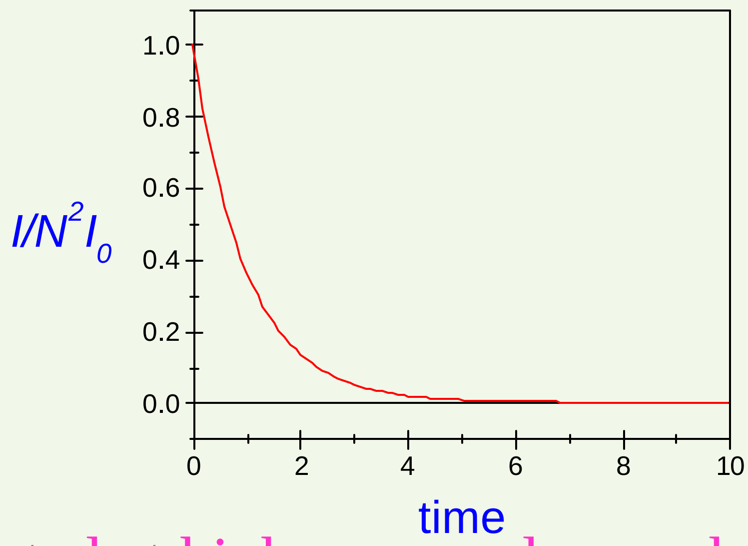
$$df_j = x_{jm} \exp(l_m t) \qquad \Rightarrow l_m = -A_e + 4|k|\sin^2 \frac{mp}{N}, \quad m = 0,1,\ldots N-1$$

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

Stability of the “In-phase” Solution

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

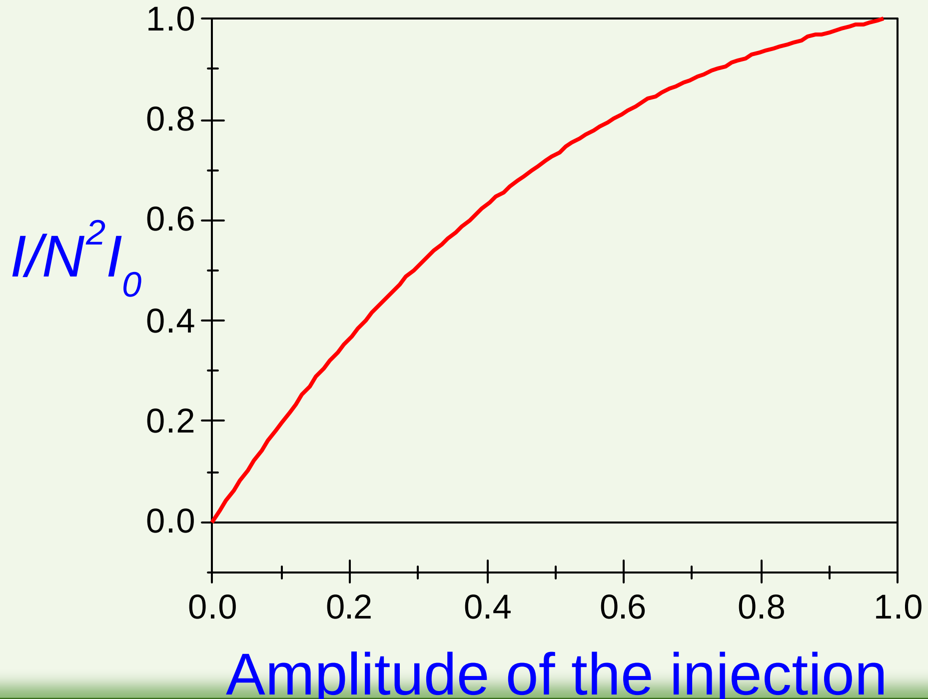
* Instead, the “Out-of-phase” solution ($\phi_{j+1} - \phi_j = \pi$) is stable, leading to a destructive interference.



* 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

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

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

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

$$d_1 + d_2 \;\square\; 0$$

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

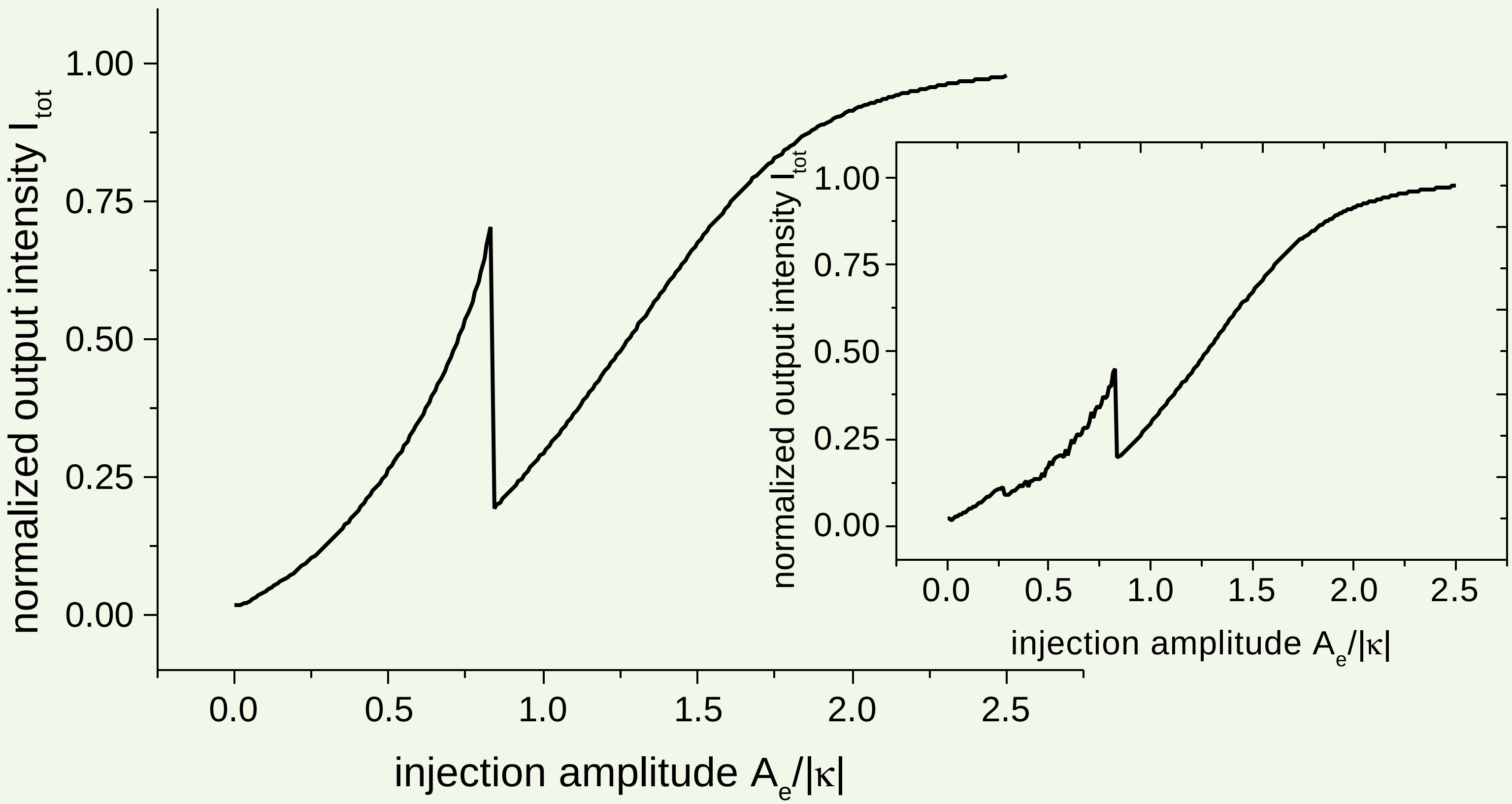
$$f(x) = -d - 2k \sin x_c - A_c \sin \frac{x_c}{2} = 0$$

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

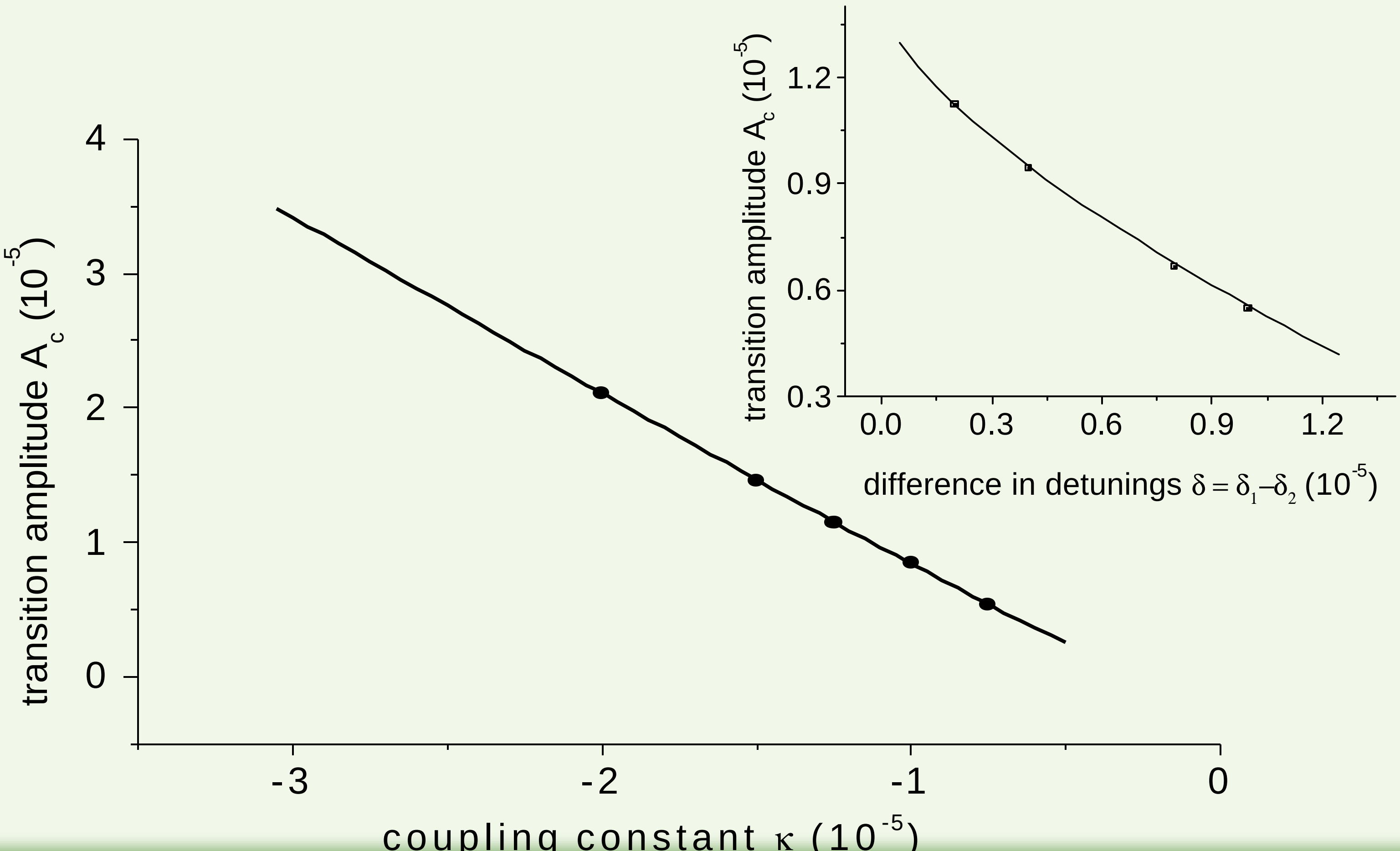
$$A_c = -2k \frac{1 - z^2}{\sqrt{1 + z^2}}.$$

$\tan x_c / 2 = z$

Nonmonotonicity



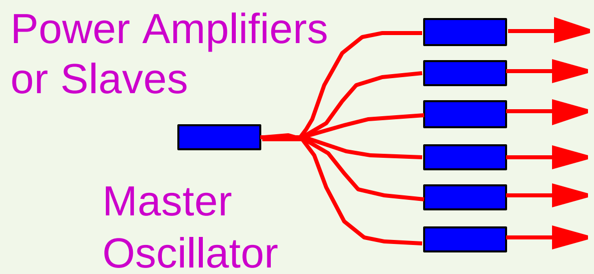
Comparison of the Analysis with Numerical Simulations



Commonly Used Array Architectures

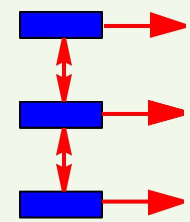
MOPA/Injection Locking

Single, stable mode from
master oscillator

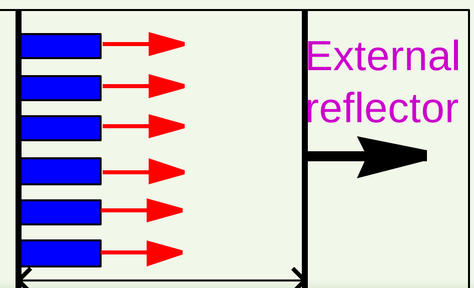


Coupled Oscillators

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



External Cavities



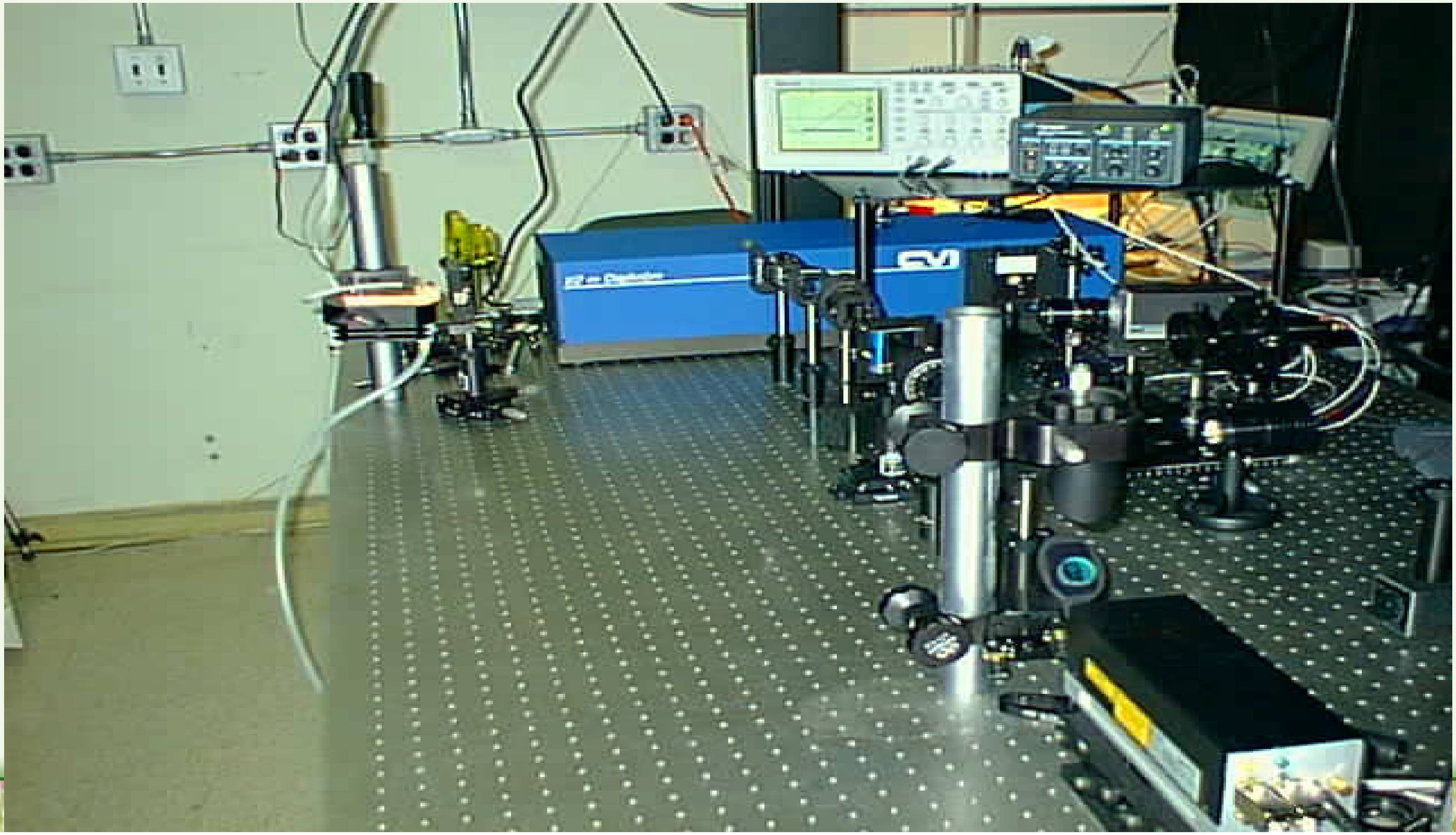
Challenges

- 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

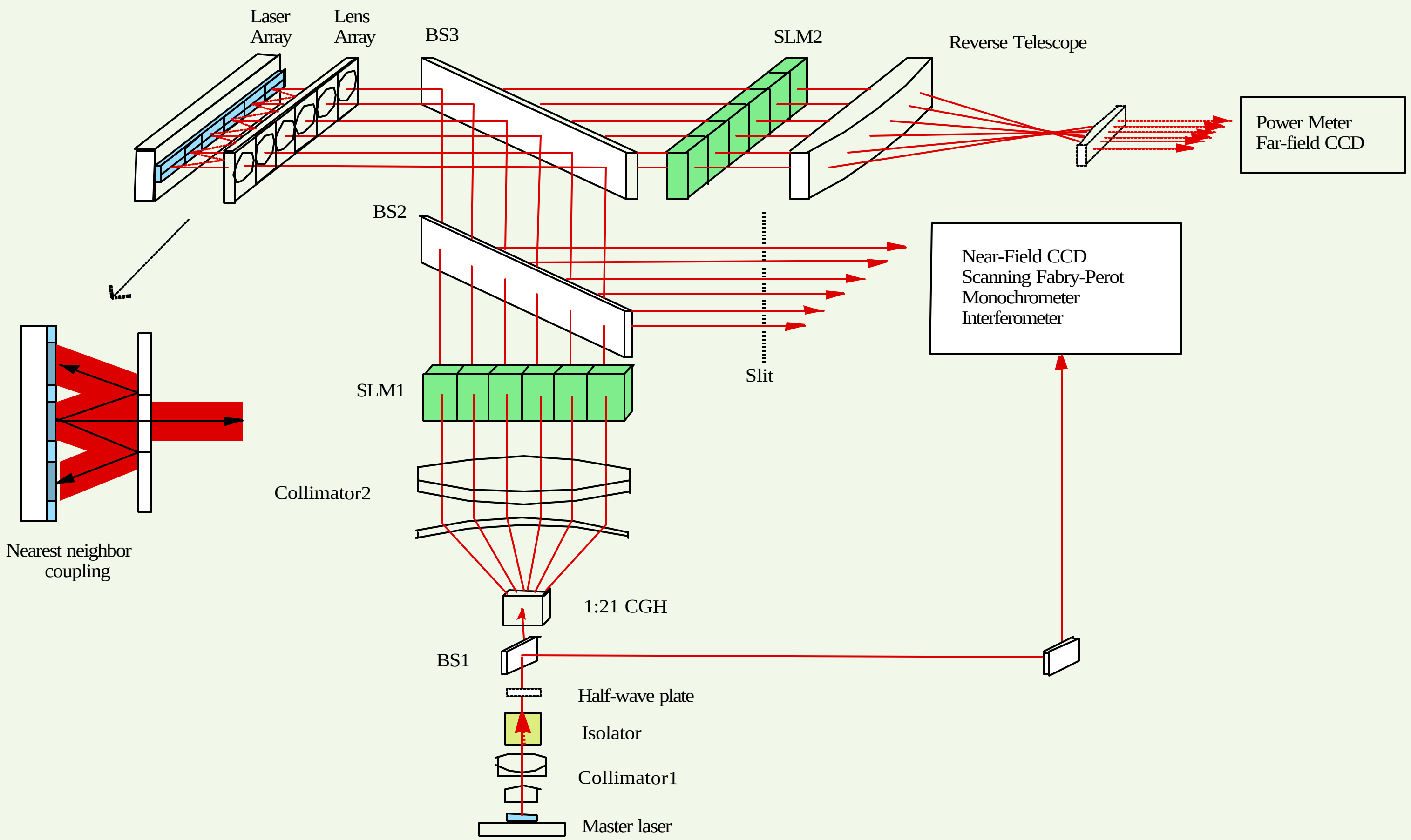
Approach

- 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

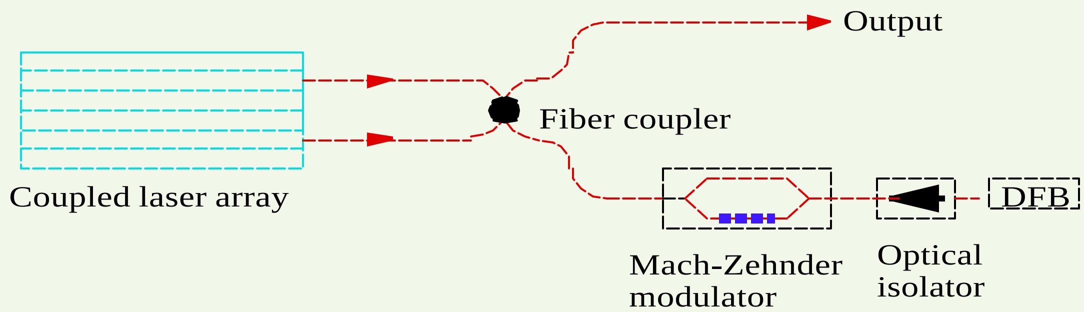


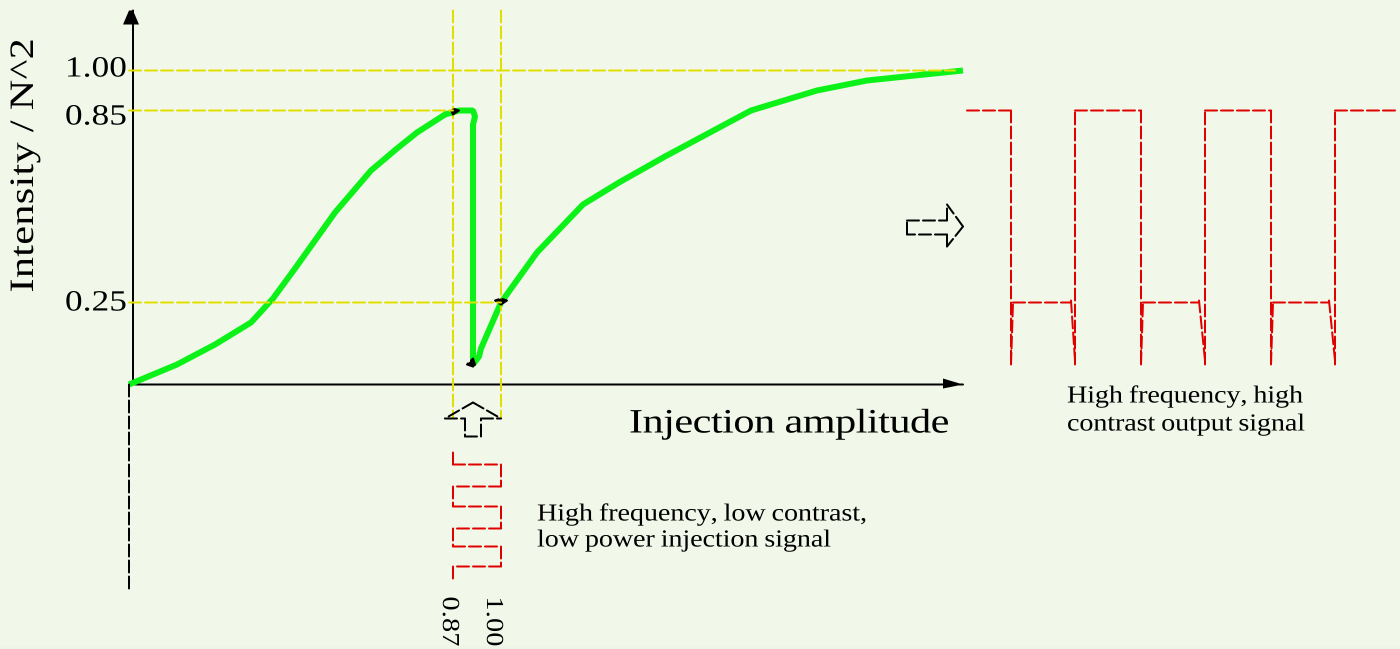
Schematic Diagram of Experiment



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).