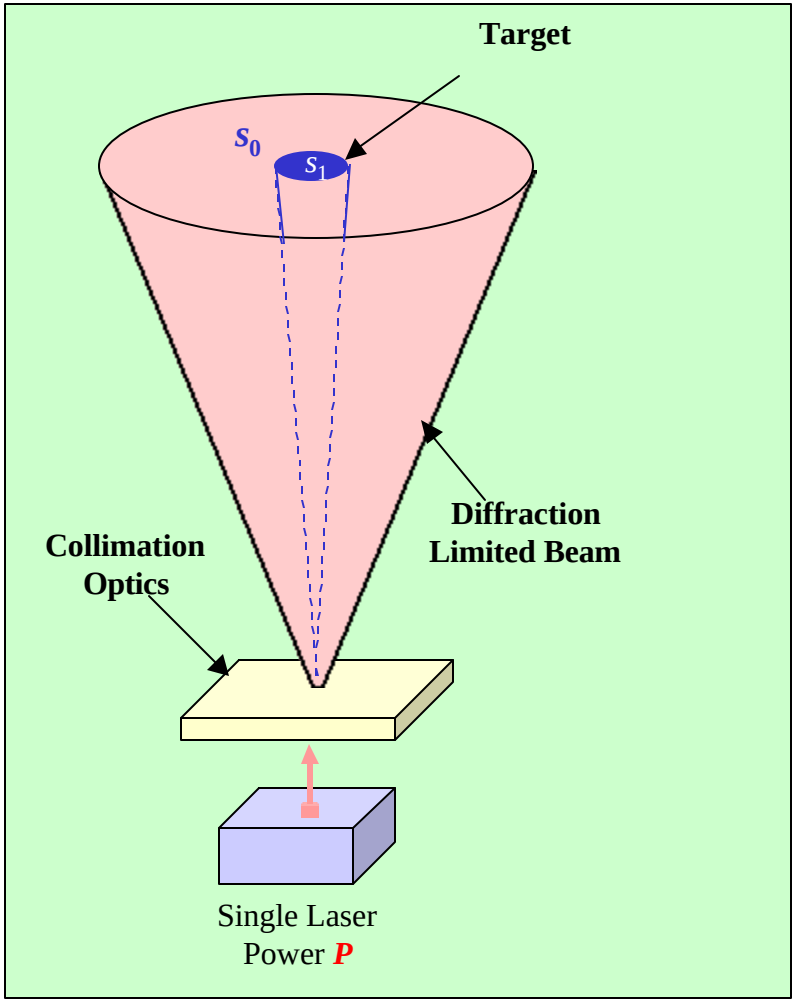
Super-High Coherent Power Generation Using Laser Arrays

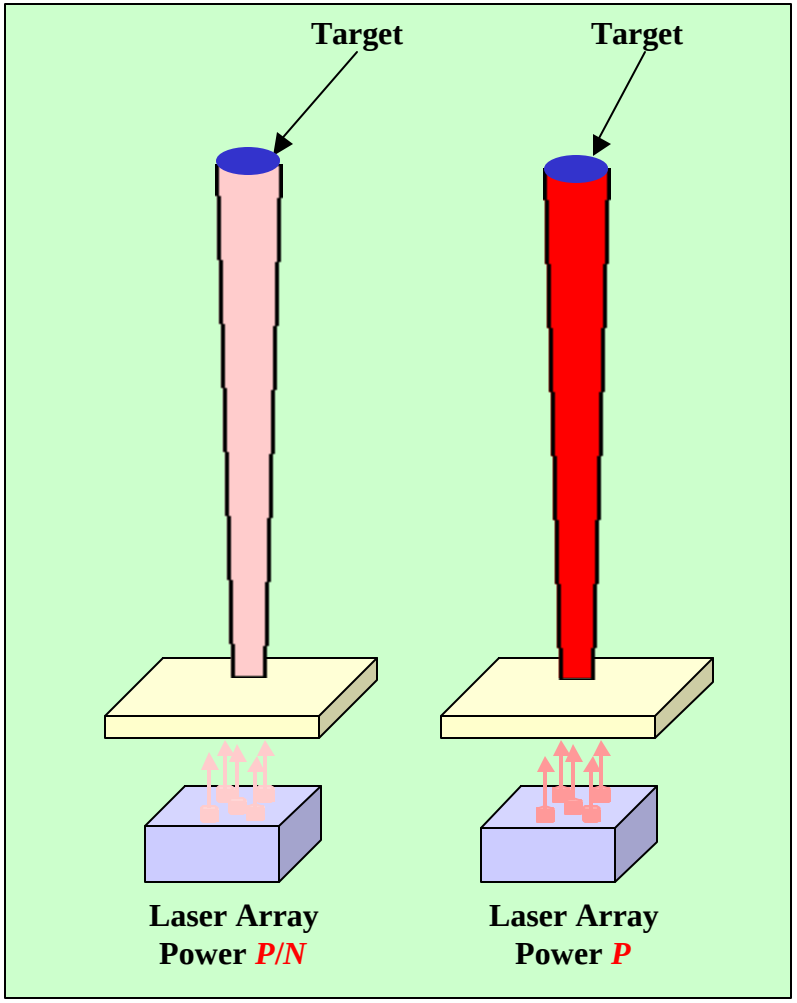
Y. Braiman, R. Garrett, Y. Liu, V. Protopopescu, and J. Barhen

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

Mike Wardlaw
Laser Technology NSWCDD/T44
Technology & Photonic Systems Branch
NSWC

Warning: This document contains information proprietary to the Oak Ridge National Laboratory, operated by UT-Battelle LLC, for the Department of Energy under contract DE-AC05-00OR22725. Unauthorized use of any portion thereof subjects the violators to prosecution under the law.





Conventional Scheme
Single Laser

Proposed Scheme
Laser Array
Intensity ~ I_0N^2

Glossary

Quantity	Standard Radio-metric Term	Popularly Used Term	Unit
Radiant Energy	Energy	Energy	Joule
Rate of Flow of Radiant Energy	Flux	Power	Watt
Radiant Intensity	Intensity	Power-in-the-bucket	Watt/sr
Areal density of radiant intensity	Radiance	Brightness	Watt/m^2 sr
Areal Density of flux incident on a surface	Irradiance	Intensity	Watt/m^2

Coherent Laser Arrays

Consider a linear array of N identical coherent laser sources. Let us denote by

- λ wavelength of emitted light
- ω laser width
- d uniform spacing between adjacent lasers

If the the lasers emit with zero phase difference, a predominantly single-lobed output beam with a far field angular divergence of about λ / Nd radians at the first nulls in the far field.

The power-in-the-bucket coming from a linear array of identical and coherent lasers will be proportional to N^2, since the total power output of the array increases as N, and the angular beam divergence decreases as $1/N$.

The relative phases between elements of the laser array can be varied in a systematic way to ensure beam steering.

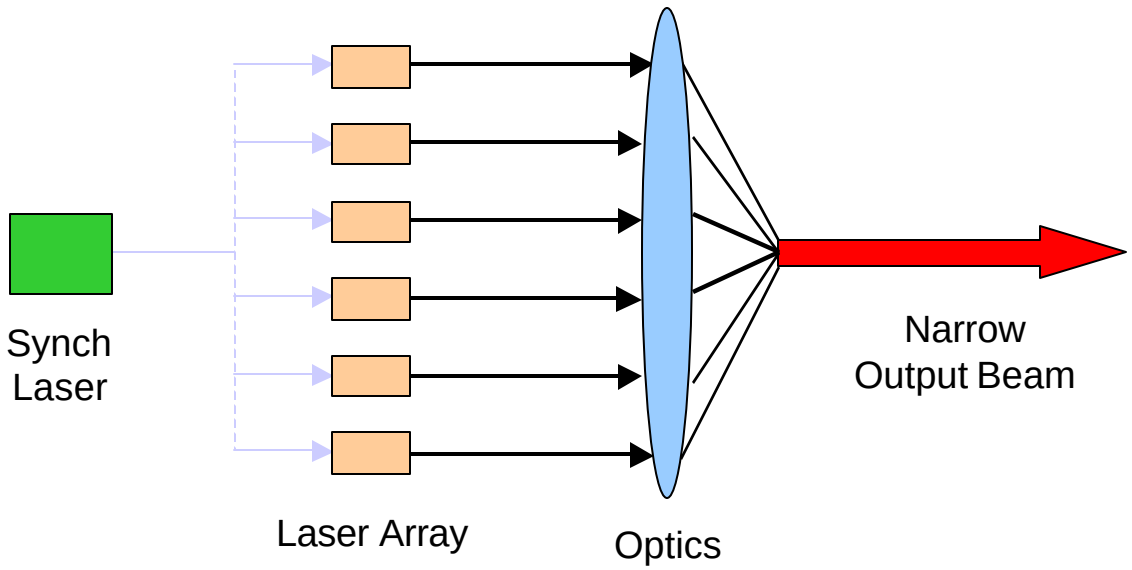
Incoherent Laser Arrays

An array of of identical lasers operating so that all elements are mutually incoherent will not give an increase in power-in-the-bucket as the array size is increased. In the case of incoherent array, the predominantly single-lobed output beam has an angular divergence λ/ω, where ω is the width of laser element of the array. The output beam divergence is determined solely by the width of the laser-array element, and is independent of the size of the array. Therefore, the photometric brightness is independent of the size of the array, and the power-in-the-bucket will only be proportional to N.

The key issue - synchronization of the laser elements in the array !

The Claim

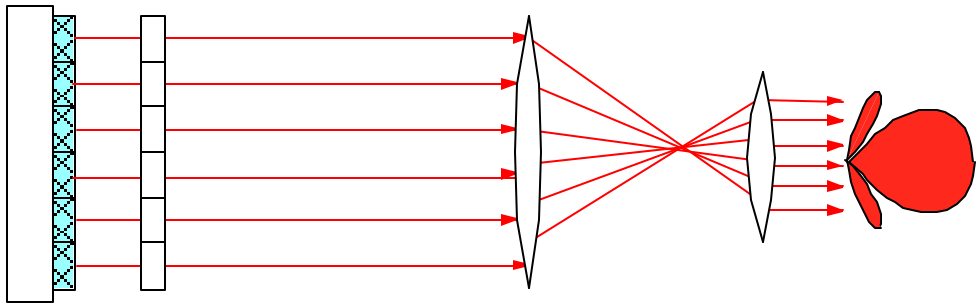
We claim that by combining N lasers into an array, synchronizing them, and properly collimating the output beam, it will be possible to obtain super high energies deposited on a small area of a moving target. This concept also accounts for beam steering that will be achieved by controlling the phases of each laser.



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).

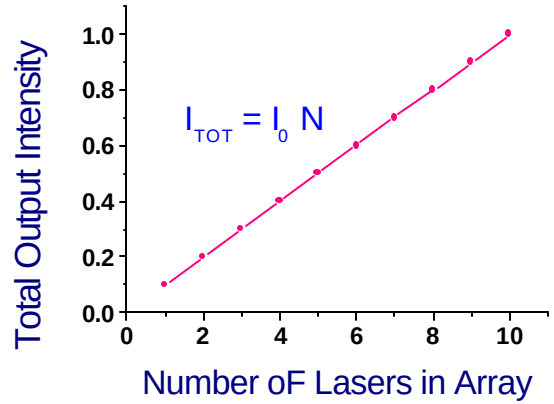
N^2 Effect

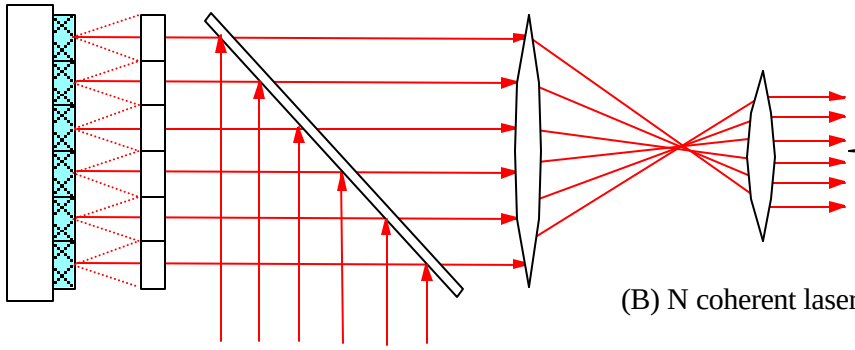


High power laser array

Microlens array

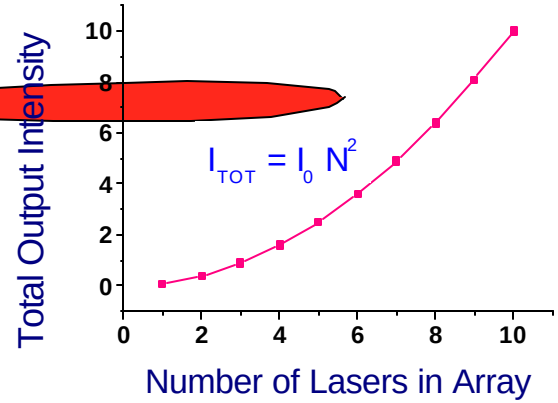
(A) N incoherent laser sources





Injection from a single frequency laser

(B) N coherent laser sources



Laser Array Synchronization

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

$$I(t) = \left|\sqrt{I_0}\exp(i\phi_1) + \sqrt{I_0}\exp(i\phi_2) + \ldots\right|^2$$

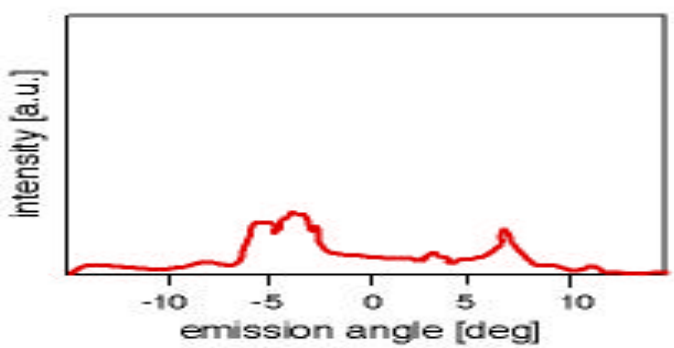
E_j - complex amplitude

ω_j - the frequency

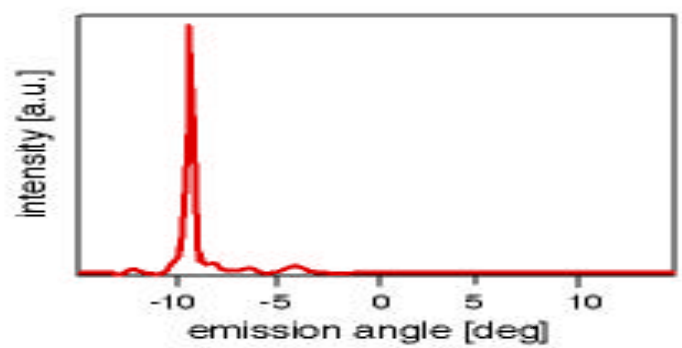
"in-phase" $\rightarrow \phi_1 = \phi_2 = \ldots = \phi_N$

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

$\Rightarrow I \sim N^2 I_0$

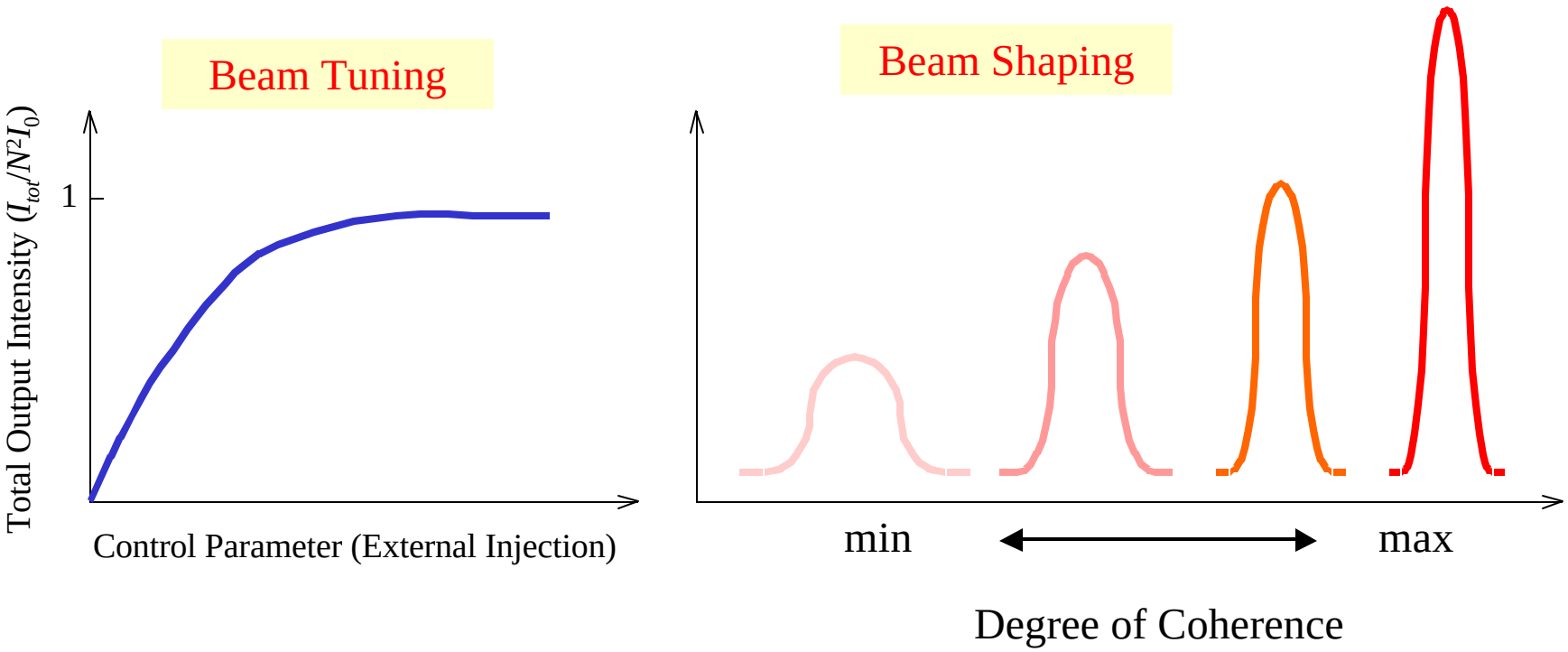


Noncoherent addition



Coherent addition

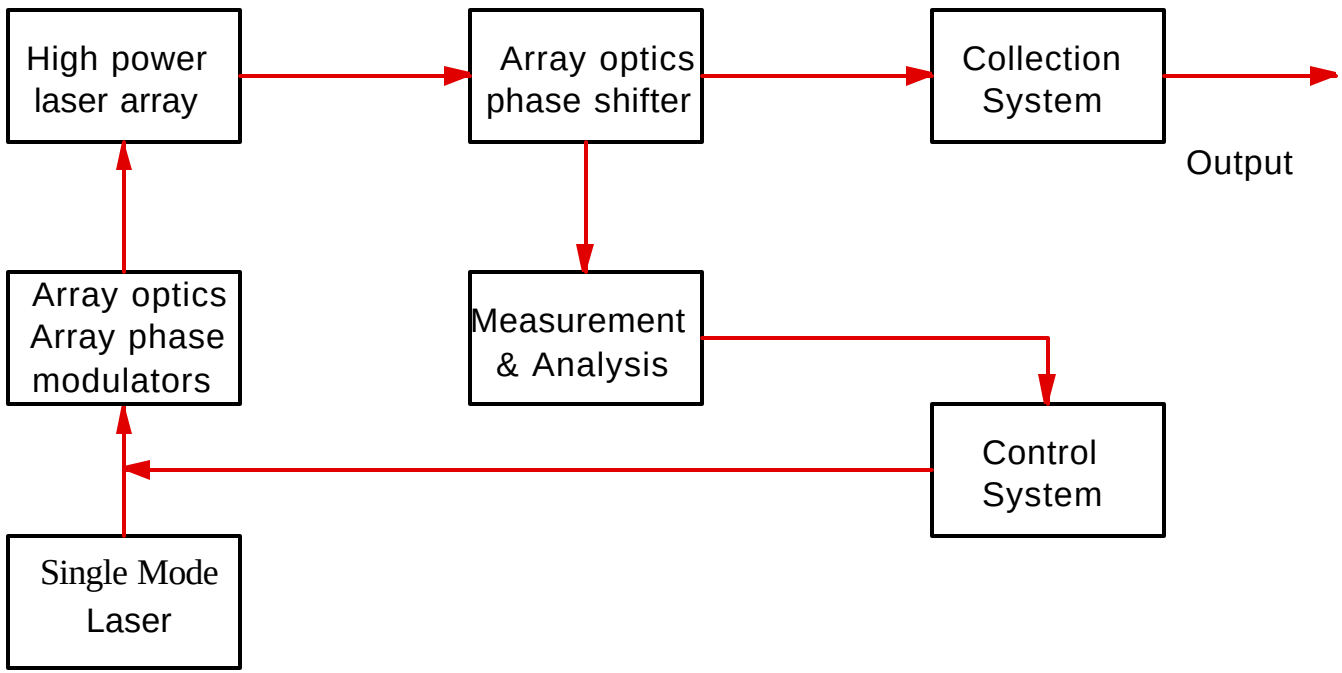
Beam Properties



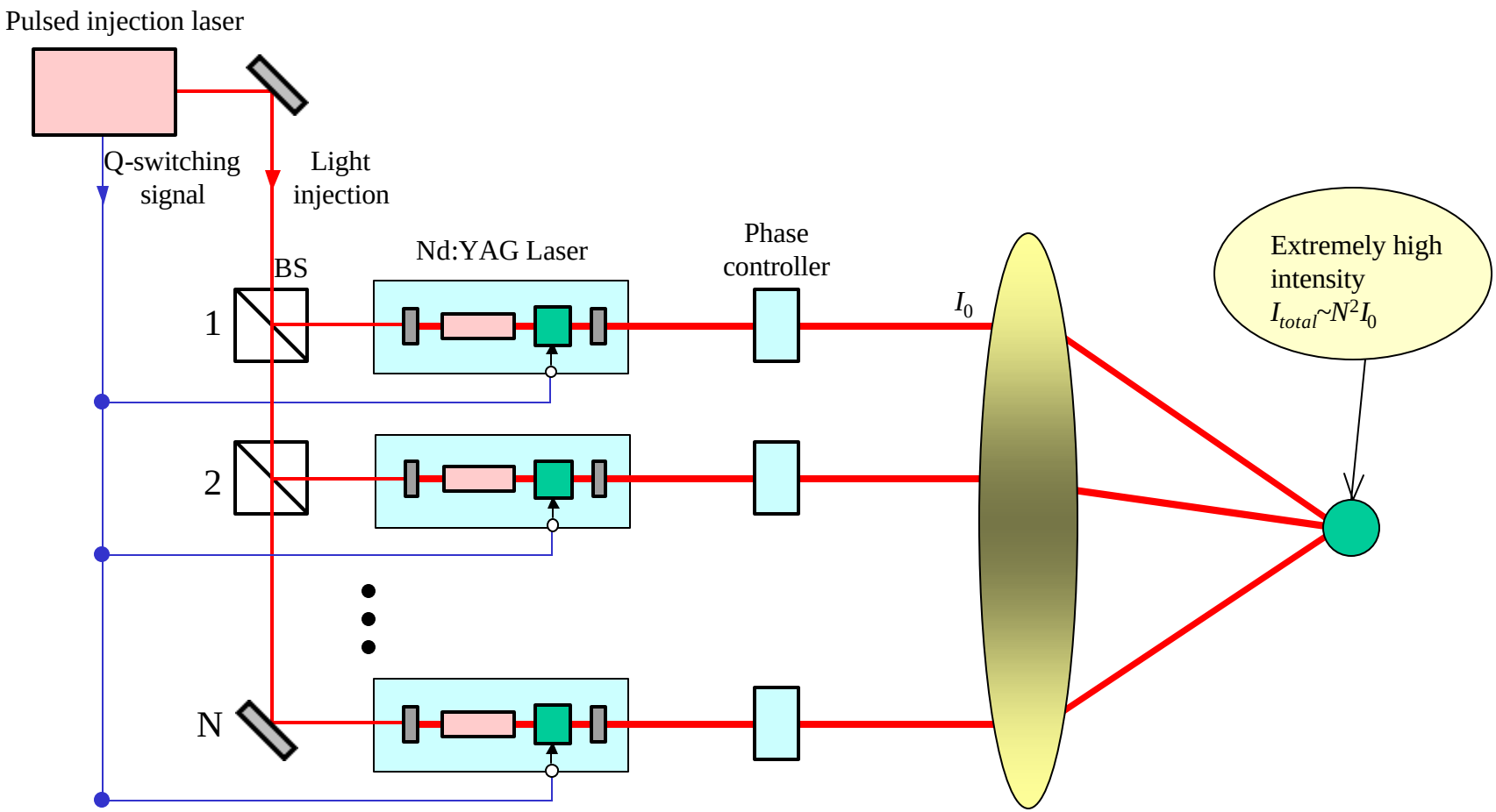
Synchronization of Solid State Lasers by Injection

- ***Injection Locking***
- ***External Cavity Coupling***
- ***Pulsing and CW Modes***
- ***Scalability***

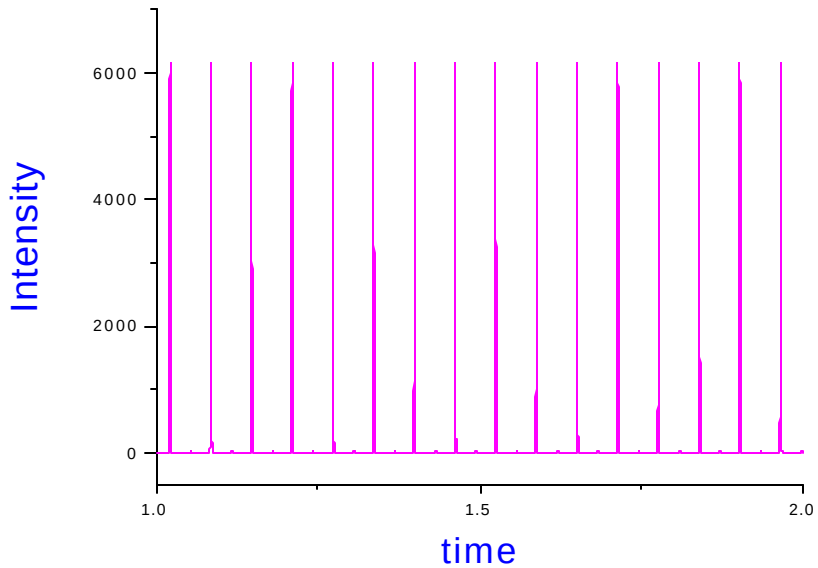
Injection Experiment



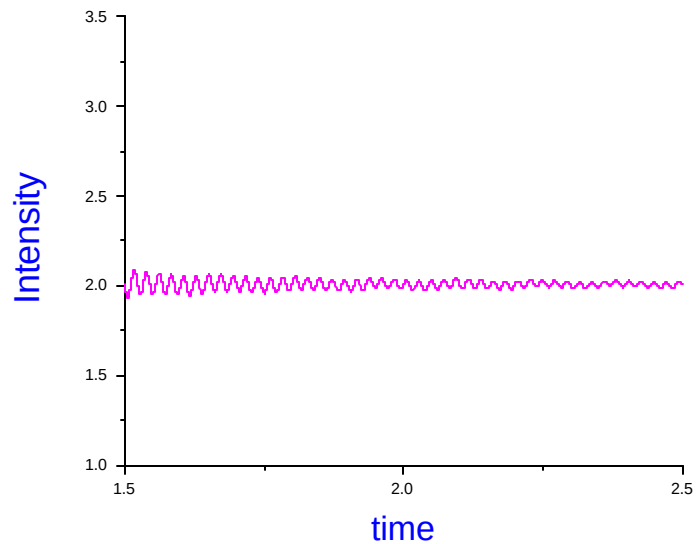
Synchronized Nd:YAG Laser Array



Synchronized Pulsing Laser Array



The intensities of five in-phase mode locked Nd:YAG lasers (as a function of time).



The intensity of a single Nd:YAG laser at CW mode (as a function of time).

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

semiconductor, solid state, CO_2, and *possibly*, chemical lasers

Rationale

- both NdYAG and CO_2 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.

Scalability

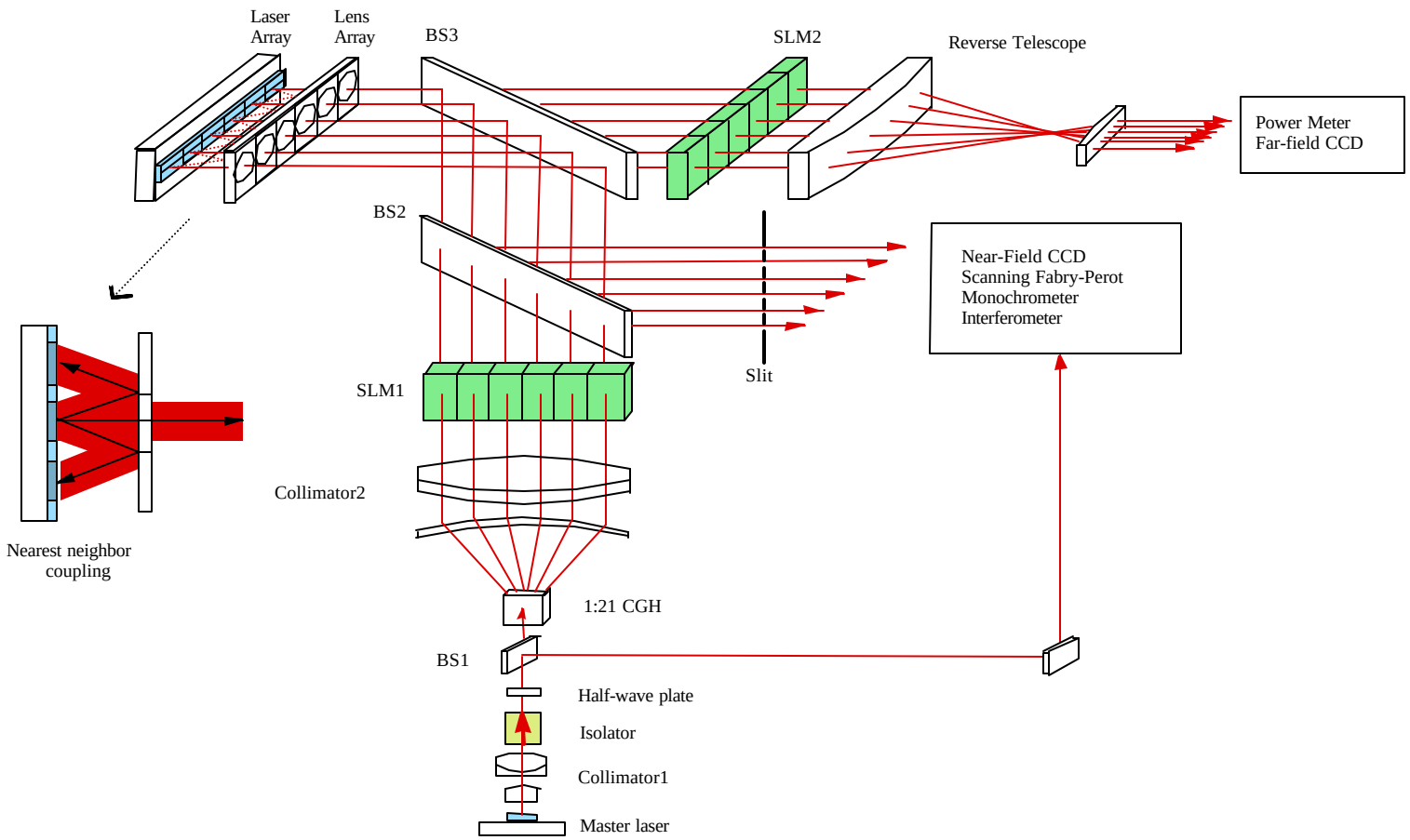
The following concepts may be tested:

- synchronization of a few (O[100]) high power (multi-mode) lasers, each emitting up to 100 W of power.
- synchronization of many (O[100-1000]) intermediate power (single mode) lasers, each emitting about 10 W of power.
- synchronization of small coupled arrays of single mode lasers.

Synchronization of High Power Broad Area Laser Arrays

- ***Injection Locking to Obtain a Single Mode Behavior***
- ***Experimental Design***
- ***Successful Implementation for Semiconductor Lasers***

Schematic Design of the Experiment



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

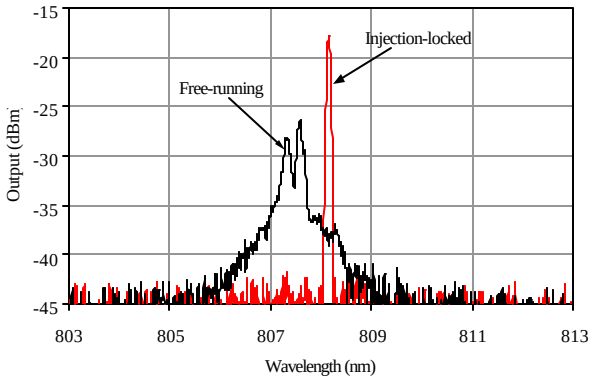
Unique Design

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

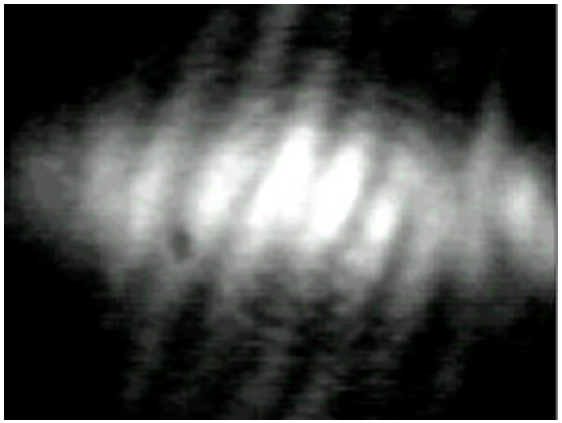
Synchronization of Two Broad-Area Laser Diodes

Optical Spectrum

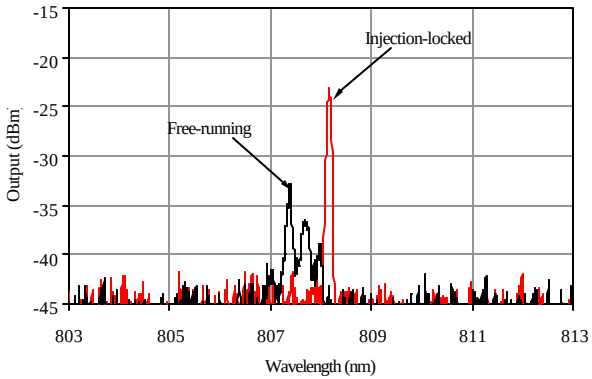
Interference Pattern



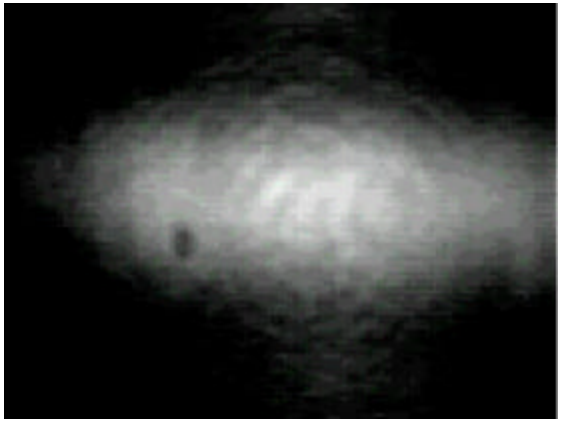
LD #7



After Synchronization

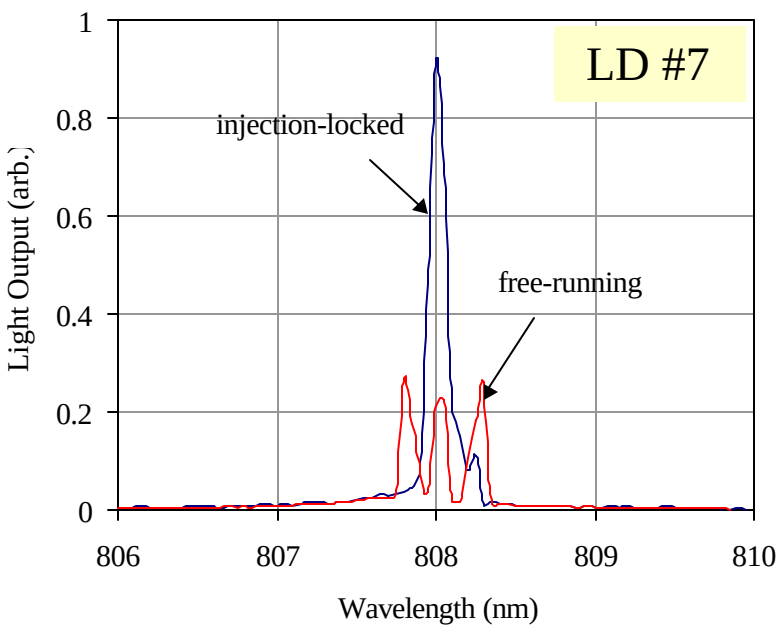


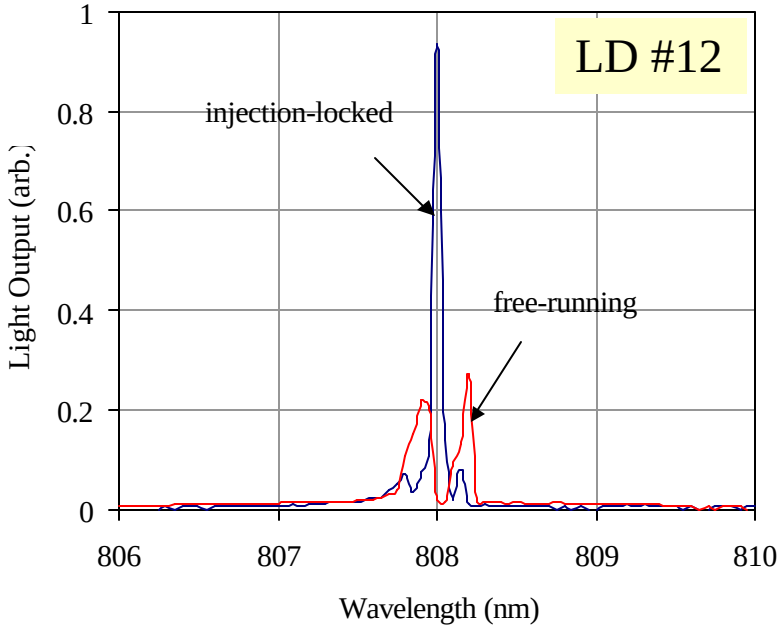
LD #4



Before Synchronization

Successful Experimental Demonstration





- Simultaneous injection-locking of two different lasers on the array with the same optical frequency
- Remarkable improvement of temporal and spatial coherence due to injection-locking

Space and Fiber Communication with High Power Laser Array

- **High Power**
- **High Speed**
- **High Contrast**

All in one device !

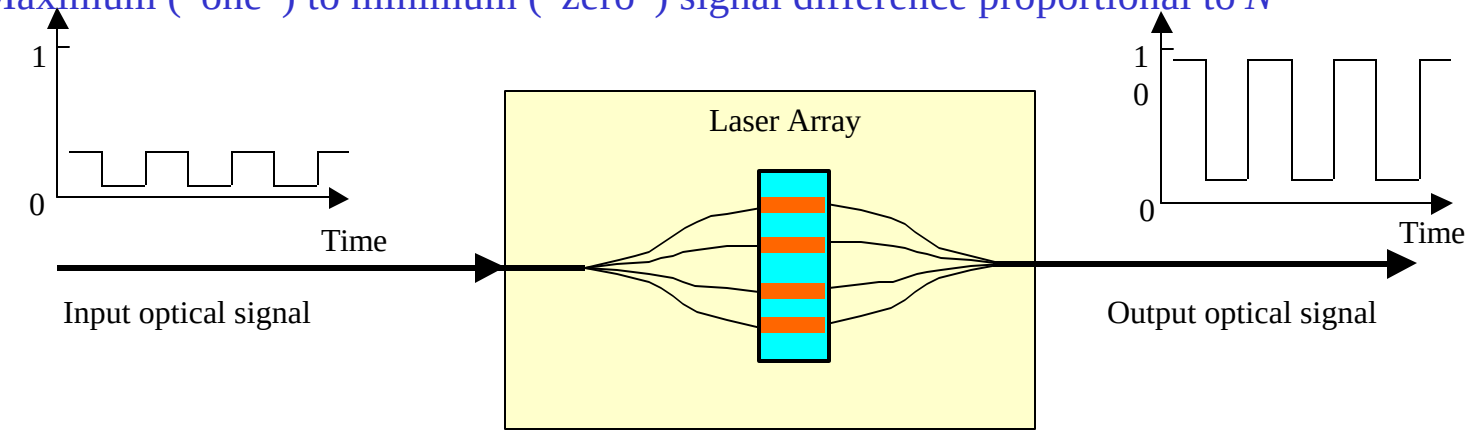
High Power, High Speed, High Contrast Communication using Semiconductor Laser Diode Array

- ***Characteristics***
  - All-optical processing, no electrical circuitry is needed
  - High-speed, high power, high contrast (all together)
  - Amplification of both optical and RF signals
  - Exactly the same output wavelength, can be easily applied to optical network

- *Technical Approach*
  - The system consists of an array of coupled semiconductor broad area (multi-mode) lasers that are controlled by an external master laser. The key issues are: (a) synchronize the array of high power semiconductor lasers to achieve a single mode coherent operation, and (b) achieve fast switching between intensity maximum and minimum to ensure high power, high contrast fast communication rates.

Implementation Schematic

Efficiency: 45% at 19W output, 25% at 5W output
Modulation rate: up to 50 GHz (internal modulation) and of the order of magnitude of 100 GHz and up (external modulation)
Average power: >10 W
Contrast: Maximum ("one") to minimum ("zero") signal ratio: >10,
Maximum ("one") to minimum ("zero") signal difference proportional to N^2



Technical Approach

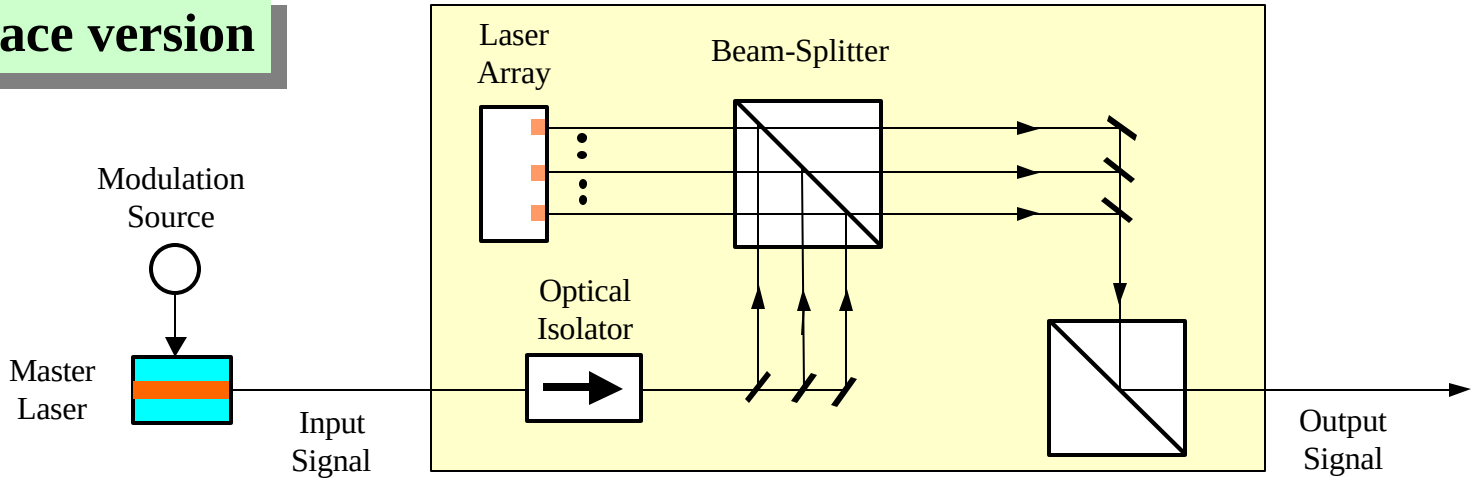
Optical injection locking of laser array
Sensitive dependency of optical phase on injection
Coherent coupling of array output

Control parameters

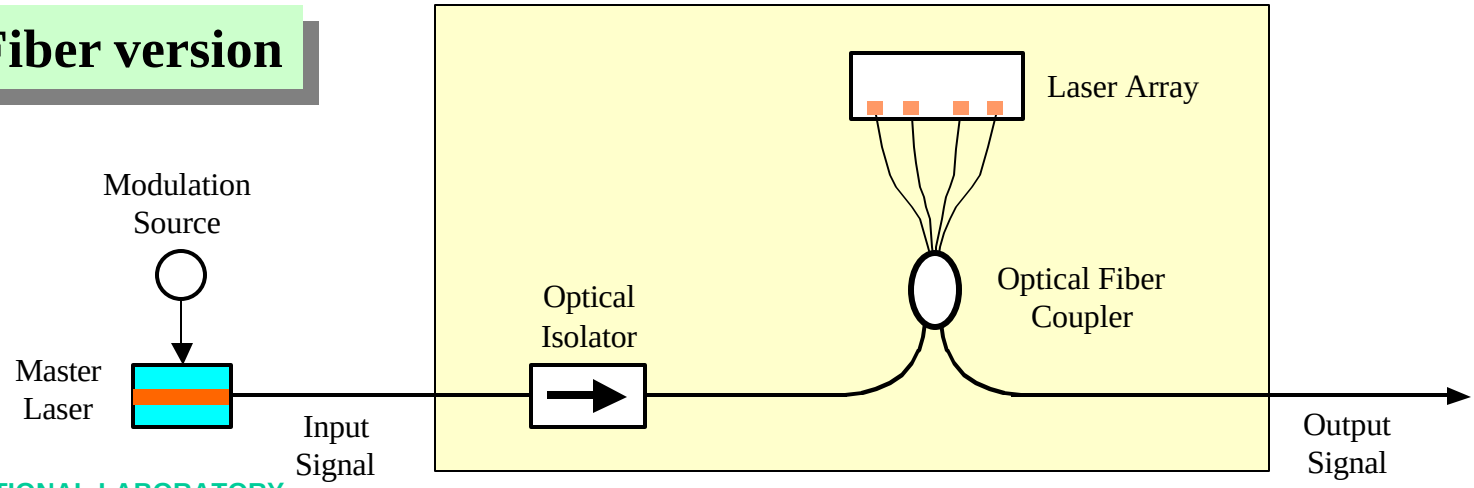
Injection current (optical gain)
Frequency detuning (RF signal gain)

Experimental Implementation Examples

Space version



Fiber version



The Team

This research brings together a very strong team with exceptional credentials for innovation and expertise in the field

- over 400 published articles
- over 30 U.S. Patents
- state-of-the-art CESAR laser laboratories

The effort under consideration involves

- unique experimental design
- unique ability to control the dynamics of the laser array
- unique ability to combine in real-time experimental measurements with computed theoretical predictions

Optical Facilities in CESAR

Five Optics Laboratories

1. Synchronization of Semiconductor Laser Arrays
2. Synchronization of Solid State NdYag Lasers*
3. Quantum Teleportation
4. Quantum Optics*
5. Optical Computing

* Being established

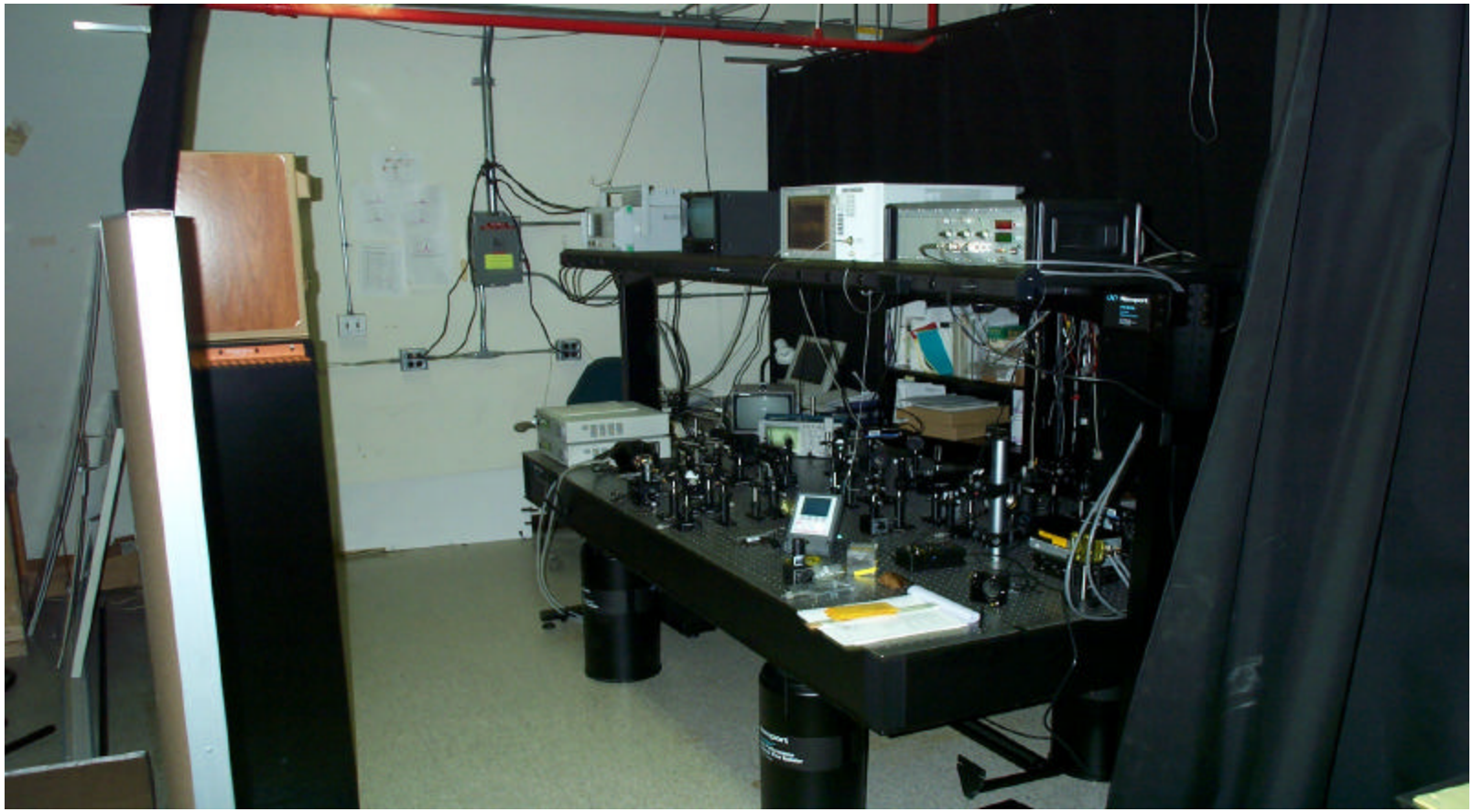
People

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)

Optical Facilities at CESAR



What Can We Do for the BMDO ?

Proof of concept demonstration

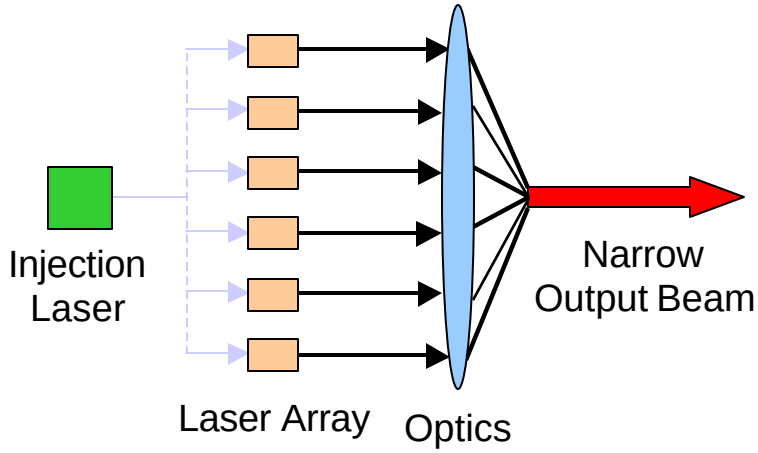
1. Optics Design
2. Scalability studies
3. Scalability Experiments
4. Demo design
5. Demonstration

MISSION AREA: Directed Energy Systems
PROPOSED PROJECT TITLE: Ultrabright Directed Energy Source

Capabilities of proposed system:

The proposed system will be able to deliver directed energy of ultra high density on target from a synchronized array of lasers.

- Scalable design consists of an array of individual lasers that can deliver a power density that scales as N^2 (N is the number of lasers in array), and is proportional to the power of each laser.
- Peak power density of MW - GW per cm^2 range.
- Can be operated continuously or in a pulsed mode with power and beam shape adjustable to application needs.



Schematic Coherent Laser Array Concept

Proposed technical approach

The system consists of a one or two dimensional array of coupled lasers controlled by an external master laser. The key issues are: (a) synchronize the array of high power lasers to achieve a single mode coherent operation, and (b) coherently collect all the beams.

Synchronization of two broad area (multi-mode) lasers has already been demonstrated at ORNL.

Corporate Description

This work would be performed at Oak Ridge National Laboratory's (ORNL) **Center for Engineering Science Advanced Research** (CESAR). ORNL is operated for the Department of Energy by UT Battelle.

Schedule & Deliverables

FY 02. Demonstrate experimentally controlled injection into array of high power lasers operating in a pulsed mode and simulate the dynamics of the array.

FY 03. Demonstrate synchronization of array in pulsed mode at low power.

FY 04. Demonstrate synchronization of array in pulsed mode at high power.

UT-BATTELLE

MISSION AREA: High Speed High Reliability Communications Systems
PROPOSED PROJECT TITLE: Coherent Laser Array for Communications

Capabilities of proposed system

The proposed system will provide a fast, reliable, and compact source for space and fiber optical communication using a synchronized laser array.

Combines the following capabilities in one unit:

- High power density for transmission achieved by synchronizing the array to obtain N^2 scaling in beam intensity. (N is the number of lasers in the array)
- High data rates (>GBPS) realized by direct current modulation or optical injection field by electro-optic modulator (EOM).
- Ultra high contrast based on non monotonous response of the synchronized array to injection light.

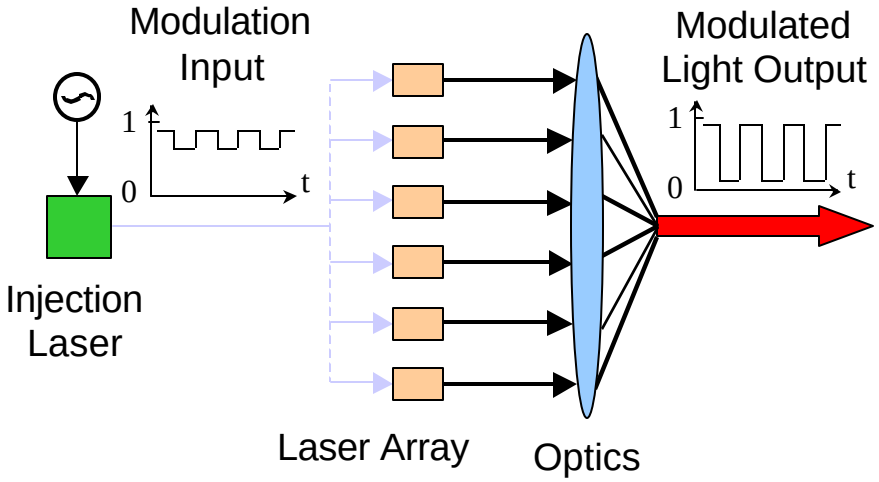
Proposed technical approach

The system consists of an array of coupled semiconductor broad area (multi-mode) lasers that are controlled by an external master laser. The key issues are: (a) synchronize the array of semiconductor lasers to achieve a single mode coherent operation, and (b) achieve fast switching between intensity extrema.

Synchronization of two broad area (multi-mode) lasers has already been demonstrated.

Corporate Description

This work would be performed at Oak Ridge National Laboratory's (ORNL) **Center for Engineering Science Advanced Research** (CESAR). ORNL is operated for the Department of Energy by UT Battelle.



Schematic Coherent Laser Array Concept for communications

Schedule & Deliverables

FY 02. Demonstrate experimentally controlled injection into array of broad area semiconductor lasers in CW mode.

FY 03. Demonstrate low data rate communication under high contrast and high power.

FY 04. Demonstrate optical communication at GBPS rates under high contrast and high power.

UT-BATTELLE