Coherent Beam Combining of 21 Semiconductor Gain Elements in a Common Cavity*

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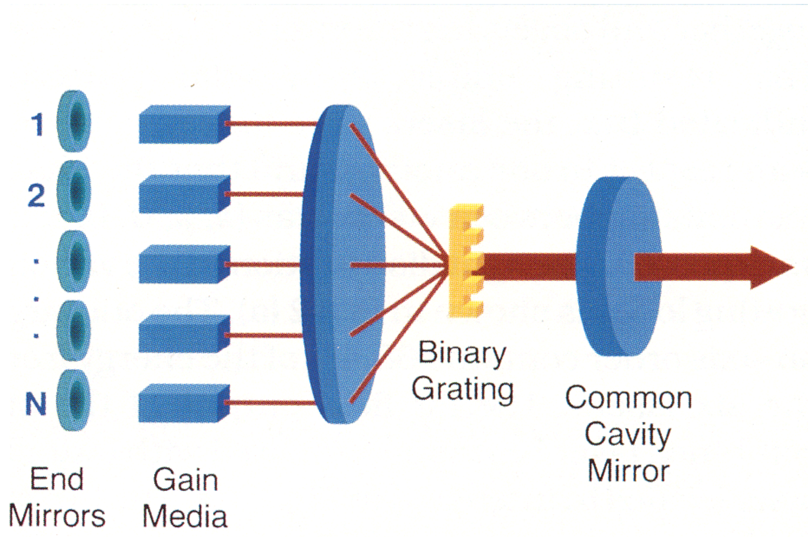
Overview

- **Array of gain elements inside a common optical cavity – an old concept for scaling with diffraction limited beam quality**
- **Scalability in earlier proof-of principle demos was hampered by the need to maintain phase across the array**



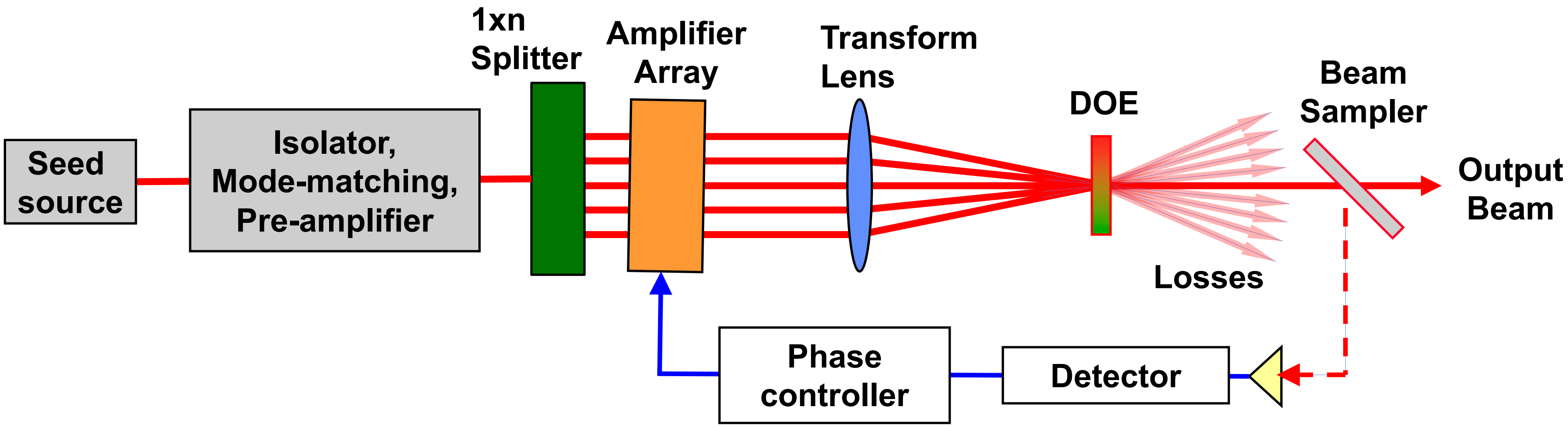
- **Number of elements (3 - 6)**
- **Combining efficiency (70% - 80%)**
- **Power ~10 mW per element**

J. R. Leger, G. J. Swanson, W. Veldkamp, “Coherent laser addition using binary phase gratings,” Appl. Opt. **26**, 4391 **(1987)**

In this work: Active control of the phase allows for scaling to 21 elements with excellent beam quality.

Master Oscillator Power Amplifier (MOPA) Configuration

- **MOPA configuration requires multiple amplification stages with isolators and mode matching optics, but has been a successful platform for coherent beam combining.**

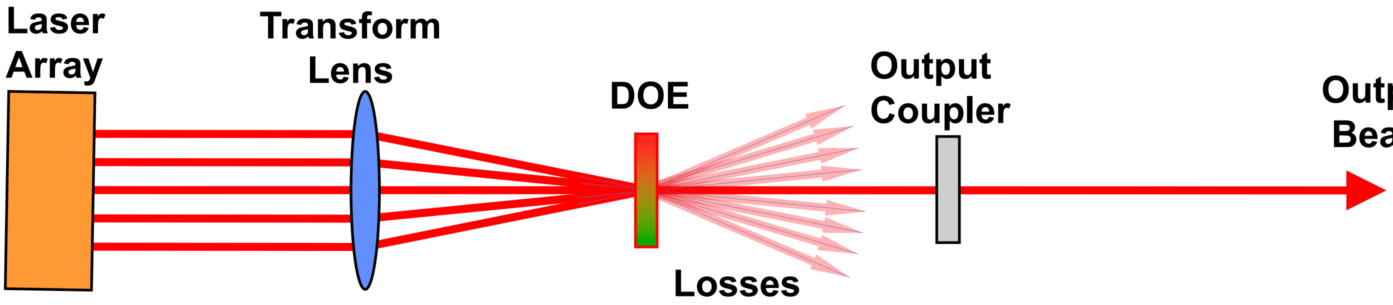


S. Redmond et al, *Active Coherent beam combining of diode lasers*, Optics Letters, Vol. 36, No. 6, 2011

MITLL has demonstrated coherent beam combining (CBC) of 218 semiconductor amplifier elements.

Power-Oscillator Configuration

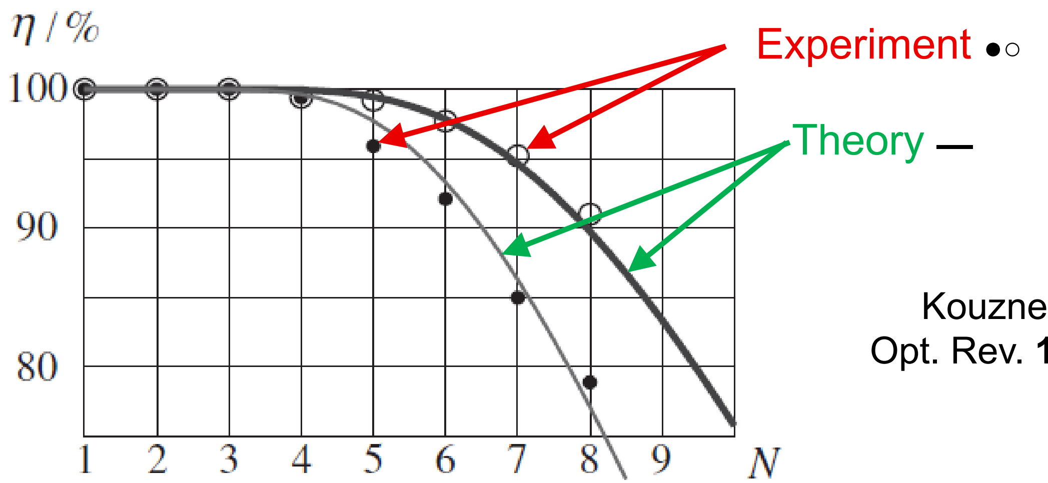
A power-oscillator is simpler and more compact than a MOPA implementation



Number Scaling of Passive CBC Cavities

- **Efficient CBC in passive cavities (no phase control of individual elements) does not scale well above ~ 8 elements**
  - **Arbitrary arm lengths cause random phase relationships**

BC efficiency for Random Phasing

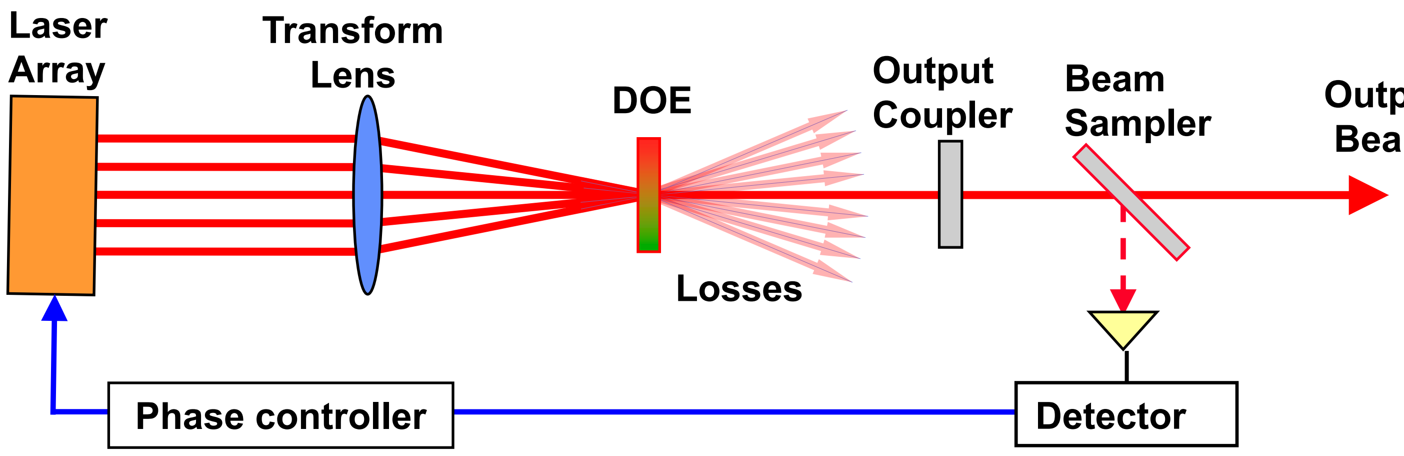


Kouznetsov, et. al,
Opt. Rev. **12**, 445 (2005)

Scaling to higher number of elements can be achieved using active phasing

Active Phase-Control Power Oscillator

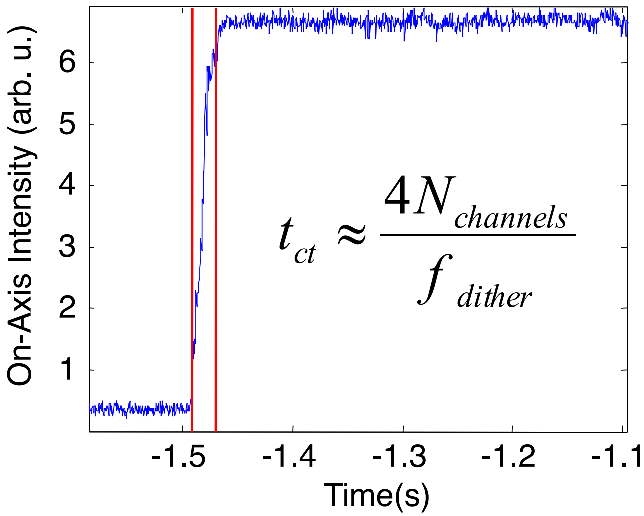
Active phase-control allows for scaling beyond passive limits

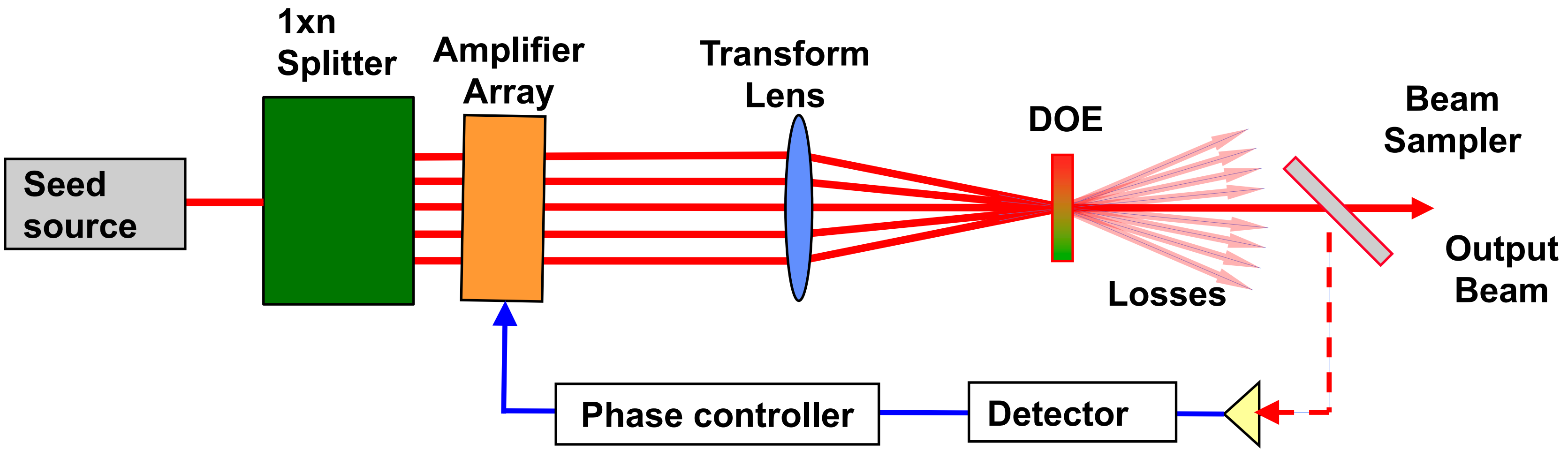


Stochastic Parallel Gradient Descent (SPGD) Phase-Control Algorithm

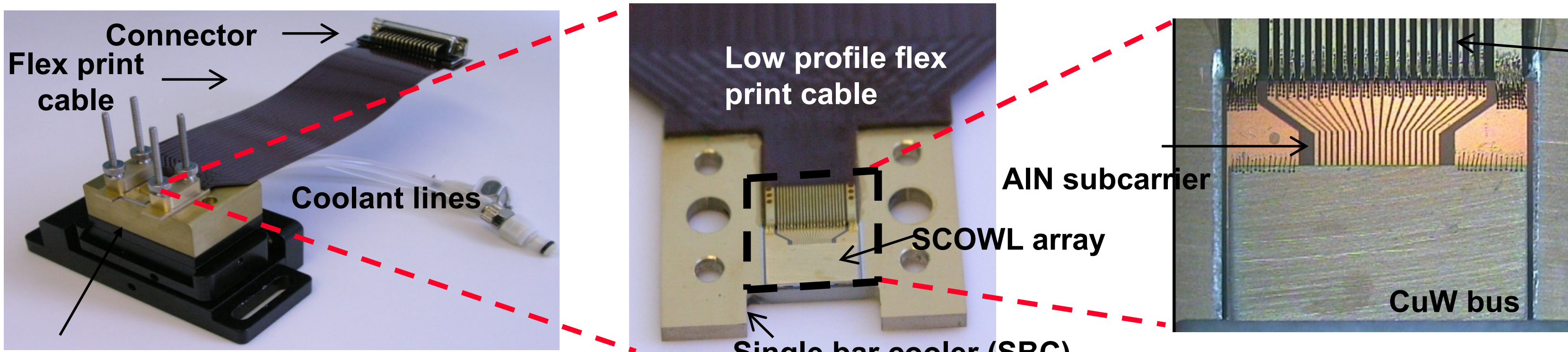
- **SPGD has enabled multiple CBC demonstrations at MIT LL**
- **SPGD is a hill climbing algorithm**
  - **Does not require a reference beam or phase knowledge**
- **Optimizes zero order output of DOE**

SPGD Convergence





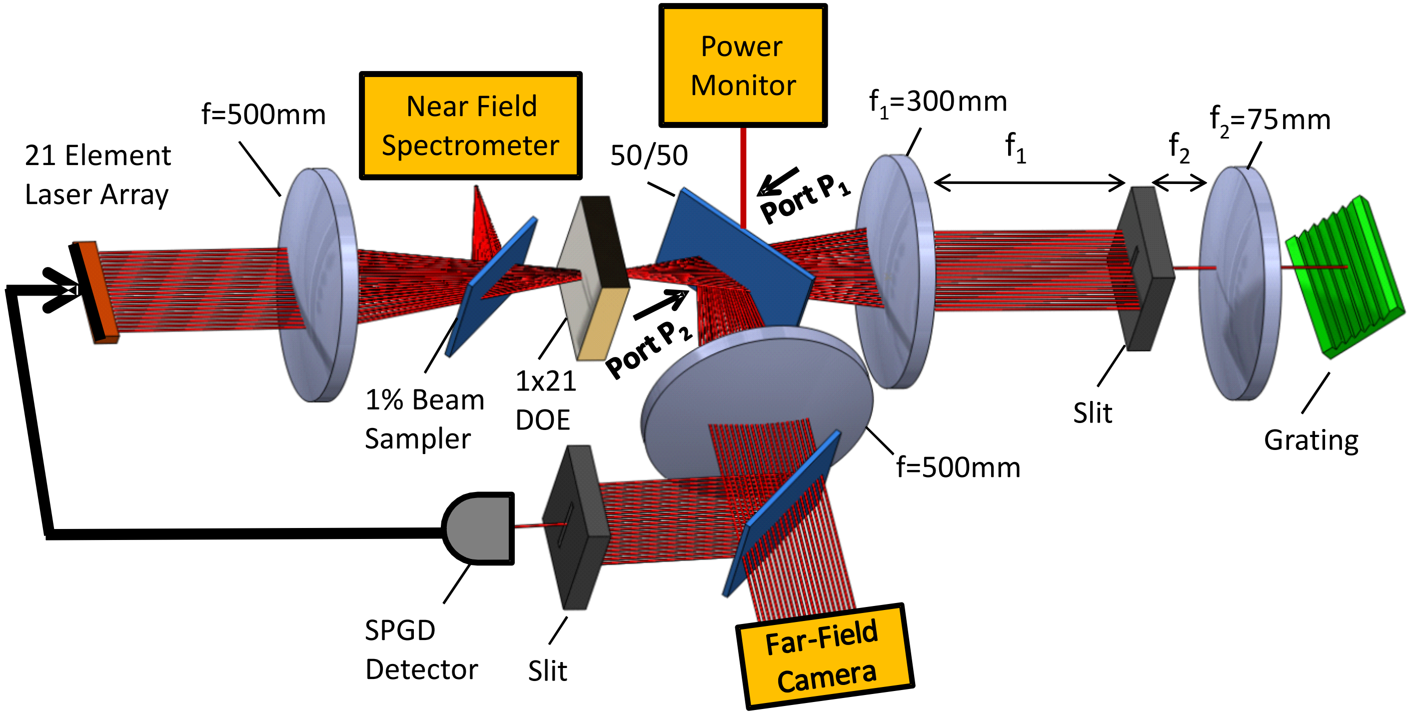
Diode Arrays with Individually Addressable Elements



- **Stackable high density arrays were developed to demonstrate coherent combination of semiconductor amplifiers:**
  - **21 individually addressable gain elements**
  - **200-µm spacing**
  - **Precise position tolerances**
  - **Back facet HR-coated and front facet AR-coated**
- **Each array is collimated with a spherical microlens array to increase the fill factor**

SCOWL – Slab Coupled Optical Waveguide Laser

21 Diode Array Combining Efficiency Measurement and Diagnostics



- Cavity output ports allow for efficiency measurement ($\eta = P_0/P_T$)
- Spatial filter (slit) prevents feedback from higher DOE orders
- Intracavity diagnostics include:
  - Near-Field Spectrometer, Far-Field Camera, Power monitors

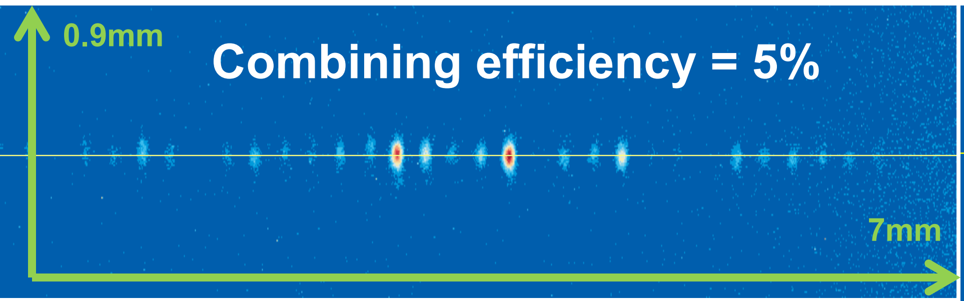
Cavity designed with diagnostics for proof-of-principle

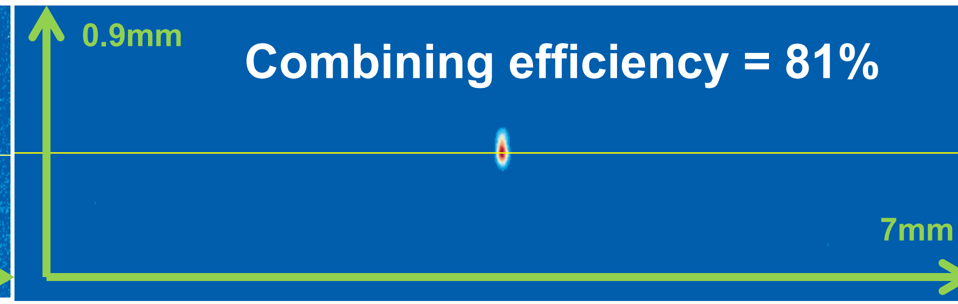
SPGD Control Loop Phase-Locks 21-Element Array

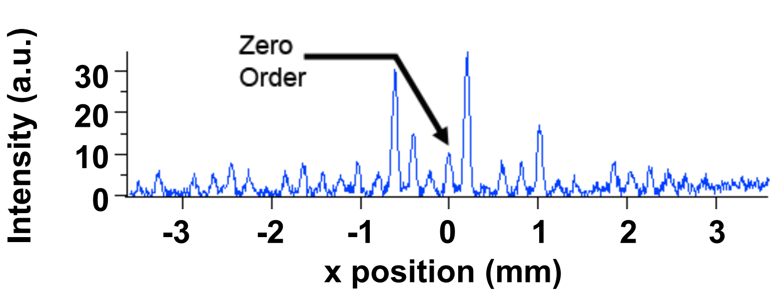
Far-field images

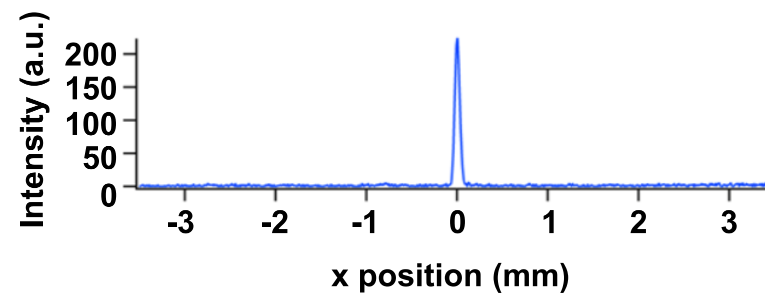
Random phase – no active control* | **With active phase control***

*Color scales normalized to show peaks, horizontal cross sections (line profiles) are not normalized







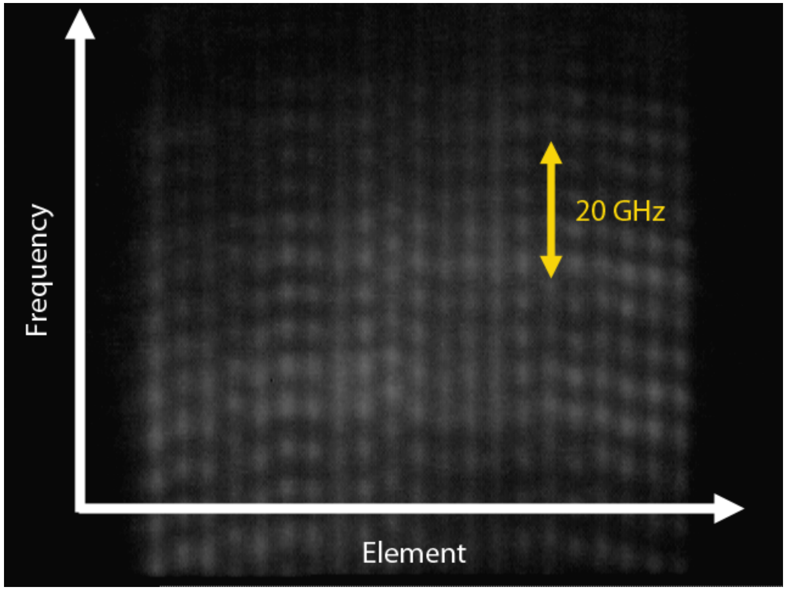


- **Random-phase combining efficiency is ~ 5%, consistent with incoherent beam combining of 21 beams**

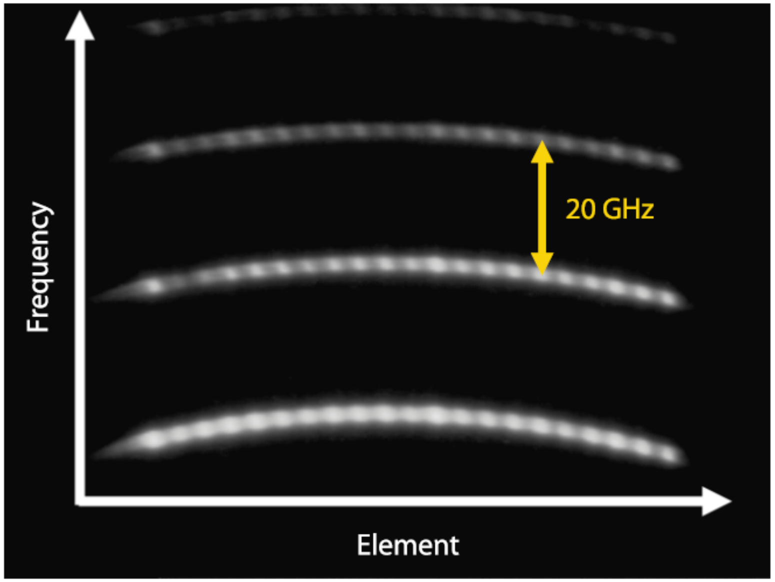
Active phase-control enables scaling to large number of elements

Near-Field Spectrometer Results

Random Phase



Active Phase Control



- **Near field spectrometer illustrates that all elements operate at the same wavelength when SPGD is activated**

SPGD adjusts optical path lengths (phase) of each emitter to coherently combine the beams

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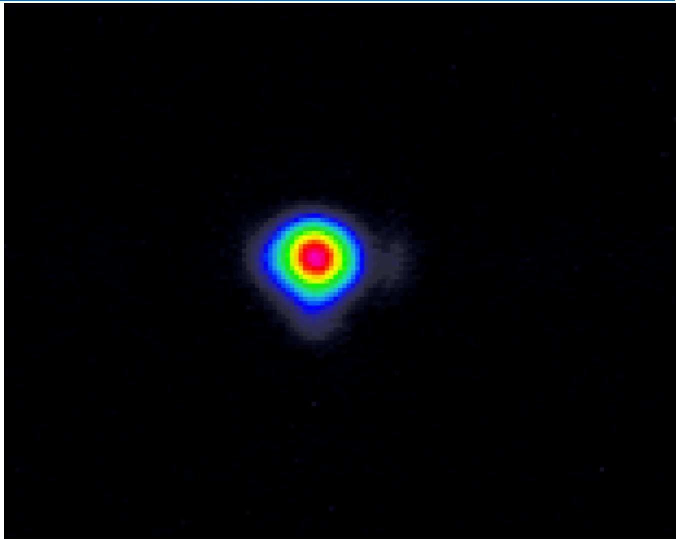
Combined Power/ Efficiency

21-Element Combined Output Power P_0 = 2.5 W, M^2=1.11

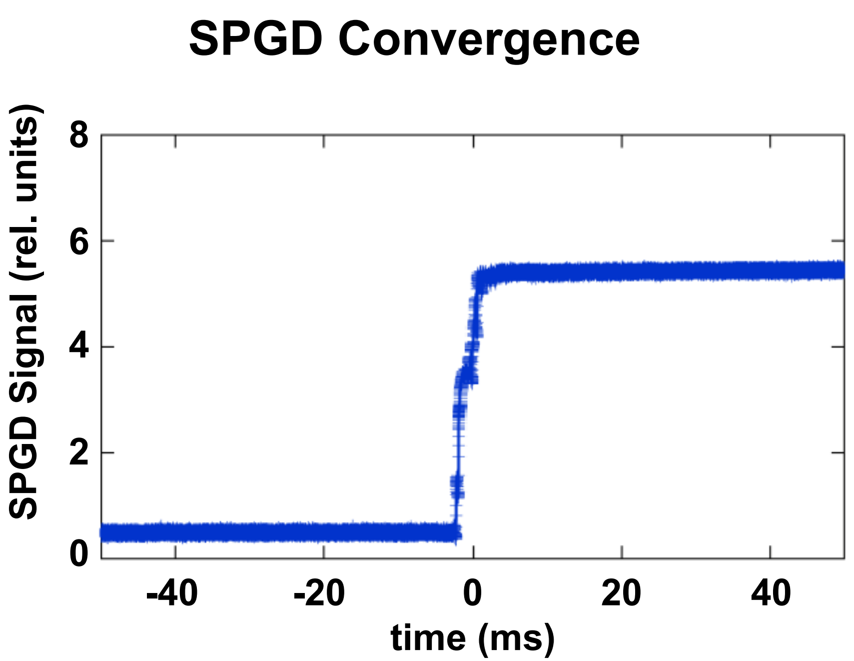


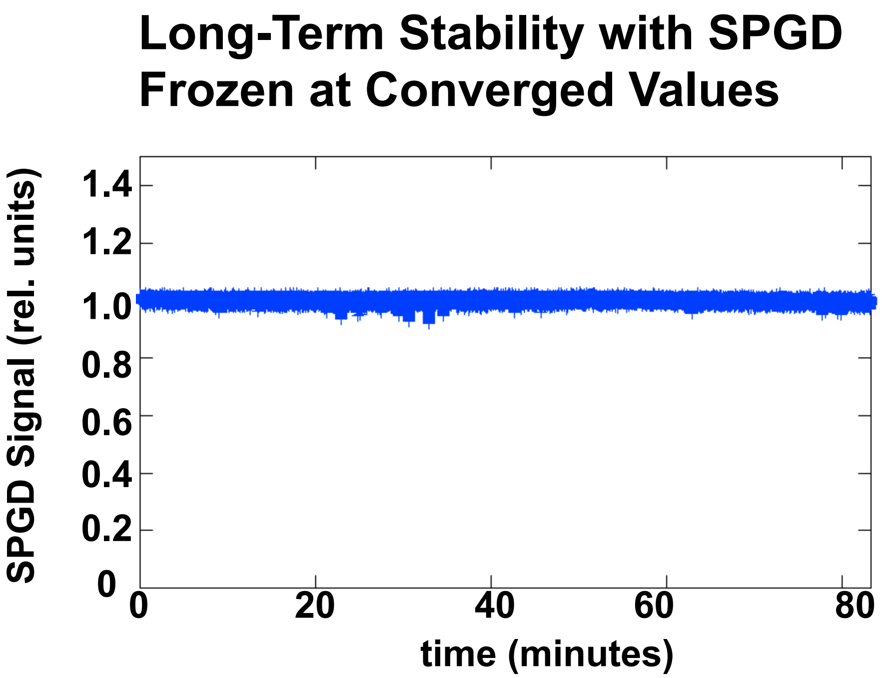
Efficiency Estimates

Loss Mechanism	Efficiency Penalty (%)	Cumulative Max Efficiency (%)
DOE splitting efficiency	10	90
Pointing Error	3	87
SPGD Dither	1	86
Aberrations	1	85
Amplitude Variations	4	81

Achieved record combining efficiencies of 81% for 21 semiconductor elements. Cavity not optimized to produce high power.

SPGD Convergence and Long-Term Stability





- **Experimentally observed convergence time ~ 4 ms**
- **Once CBC is established and phases are held fixed at optimum values, the active phase control may be turned off and efficiency is self-sustaining**

Summary

- Power oscillators are more compact than MOPA lasers
- Diode and bulk solid-state lasers are well-suited to power oscillator configurations
  - We have successfully demonstrated 21 diode element CBC in a power oscillator with an 81% combining efficiency

Acknowledgements:

- George Turner, Leo Missaggia for diode arrays
- Shawn Redmond for SPGD discussions
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