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Technical Groups

Adaptive Wavefront Control with Coherent Fiber Array Systems

Featuring Mikhail A. Vorontsov, University of Dayton

12 September 2022

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Today’s Speaker

Mikhail A. Vorontsov

University of Dayton

Dr. Vorontsov is a recognized expert in atmospheric and adaptive optics, coherent fiber-array laser systems, atmospheric imaging, and beam control. Before joining the University of Dayton as Professor and Endowed Chair in 2009, he held positions as Research Professor, University of Maryland, College Park; Director of the Intelligent Optics Laboratory, U.S. Army Research Laboratory; Professor, New Mexico State University and Professor, Moscow State University, Russia. Prof. Vorontsov founded Optonicus LLC in 2009 and was CEO until its acquisition by II-VI A&D in 2018. After this date he supported Optonicus LLC technology transition to II-VI as the Chief Scientist until August 2021. Dr. Vorontsov co-founded Optonica LLC in 2021 and serves as the company CTO. He has over 7,000 citations to >350 journal articles and several books. He is a Fellow of the Optica, ARL and SPIE.

Adaptive Wavefront Control with Coherent Fiber Array Laser Systems

Mikhail Vorontsov

Department of Electro-Optics and Photonics
University of Dayton, 300 College Park Dayton, OH 45469, &
Optonica LLC, Spring Valley, OH 45370.

Thomas Weyrauch, Ernst Polnau, Grigorii Filimonov (UD)

II-VI AEROSPACE & DEFENSE

Svetlana Lachinova, David Bricker, Yoshihiro Masui, Morris Maynard, Vladimir Ovchinnikov, Tom Tumolillo

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Discussion Topics

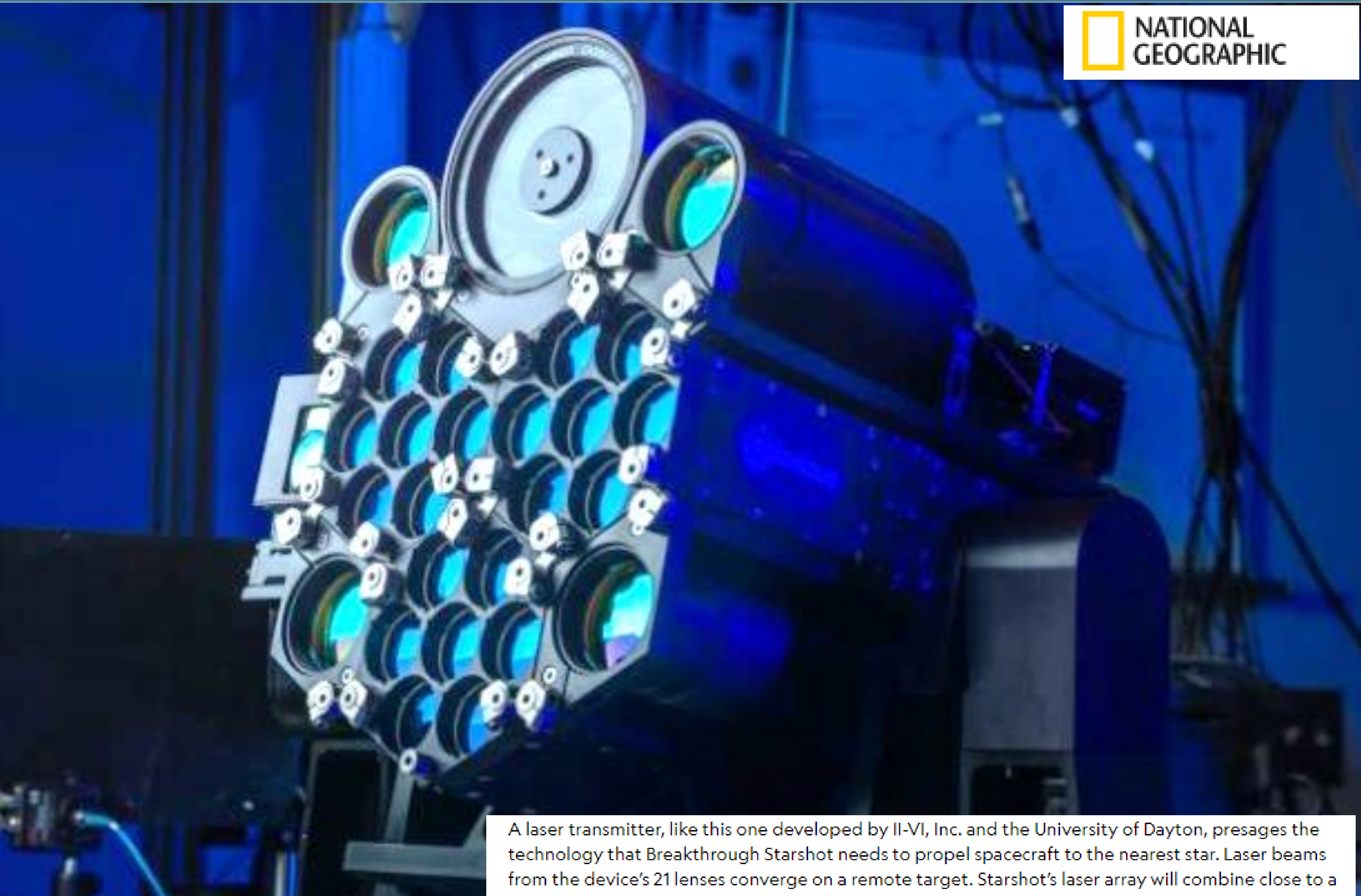
- Introduction to coherent fiber array technology
- Conventional vs coherent fiber array-based laser transmitters: pros & cons
- Example of a low-power fiber array system implementation
- High-power coherent (tiled) fiber array beam directors: major subsystems
- Target-in-the-loop coherent beam combining (CBC) with SPGD control algorithm

- Target-in-the-loop turbulence effects mitigation over 7 km with a coherent fiber array system having 21-subapertures ("cooperative" target)

- Engineering laser beams with controllable coherence using fiber array systems
- CBC on an extended (non-cooperative) target with high-speed stair-mode beam steering
- Remote laser power beaming with adaptive beam shaping
- Laser material processing & additive manufacturing with fiber array laser power sources

- Concluding Remarks

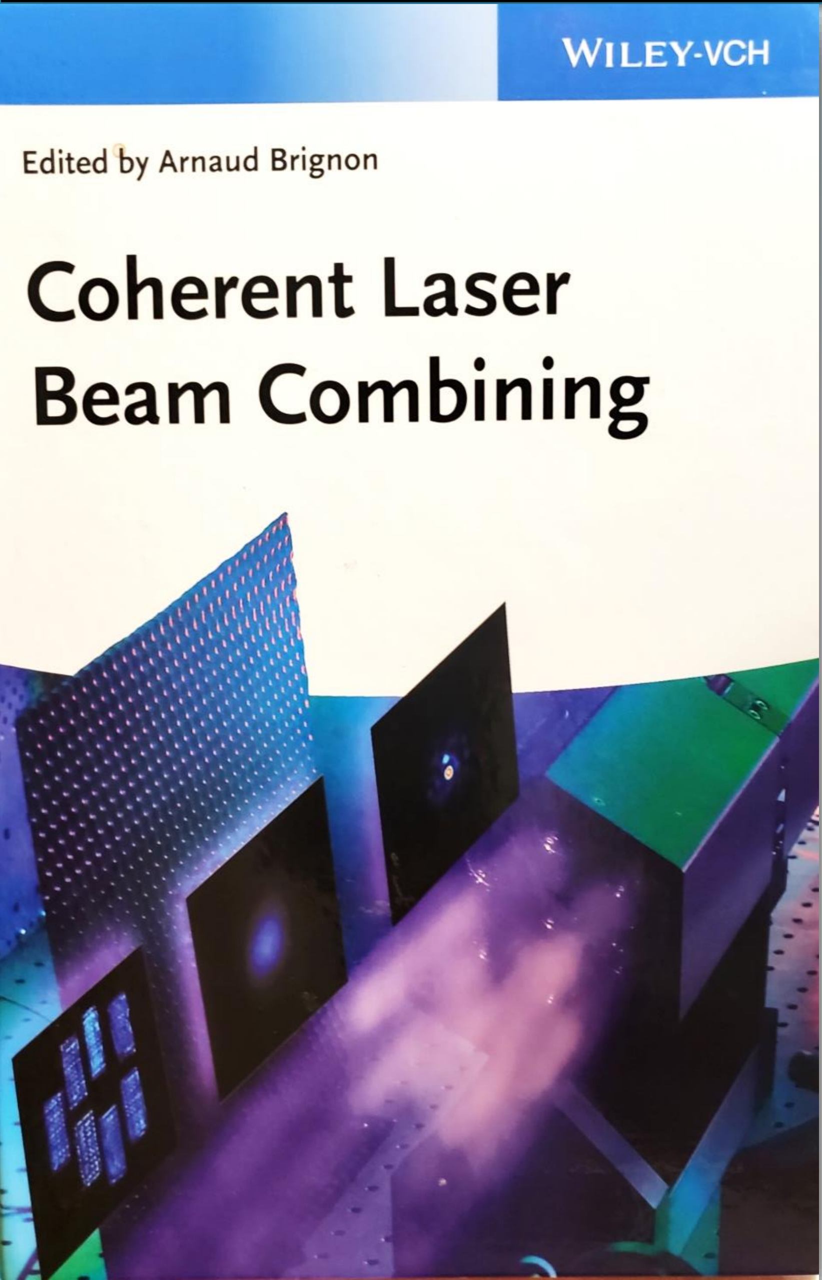
Coherent Fiber Array Laser Technology at National Geographic



NATIONAL GEOGRAPHIC

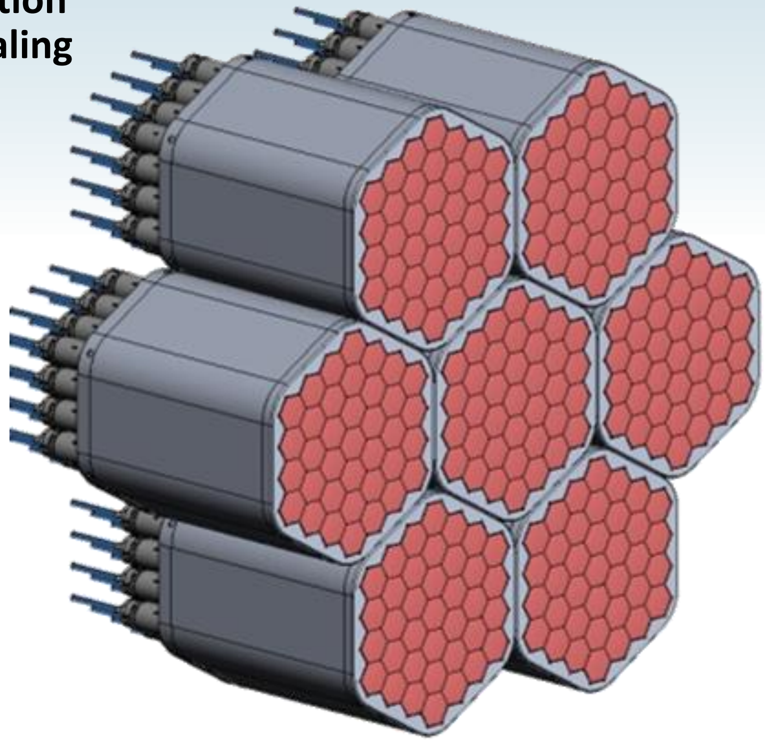
A laser transmitter, like this one developed by II-VI, Inc. and the University of Dayton, presages the technology that Breakthrough Starshot needs to propel spacecraft to the nearest star. Laser beams from the device's 21 lenses converge on a remote target. Starshot's laser array will combine close to a

Coherent Beam Combining: Selected Publications



Hossein Fathi 1, Mikko Närhi and Regina Gumenyuk, "Towards ultimate high-power scaling: coherent beam combing of fiber lasers"
Preprints (www.preprints.org); Posted: 19 November 2021

Notional illustration of fiber array scaling in power and number of beams



T. Y. Fan, "Laser beam combining for high-power, high-radiance sources," IEEE JSTQE, **11**(3), 567-577, (2005).

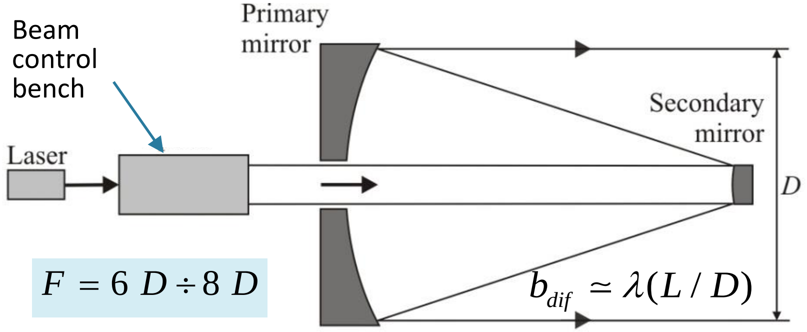
M. A. Vorontsov, "Adaptive photonics phase-locked elements (**APPLE**): system architecture and wavefront control concept," Proc. SPIE, (2005).

M. A. Vorontsov and S. Lachinova, "Laser beam projection with adaptive array of fiber collimators: Basic considerations". JOSA. A 2008, 25, 1948 (2008).

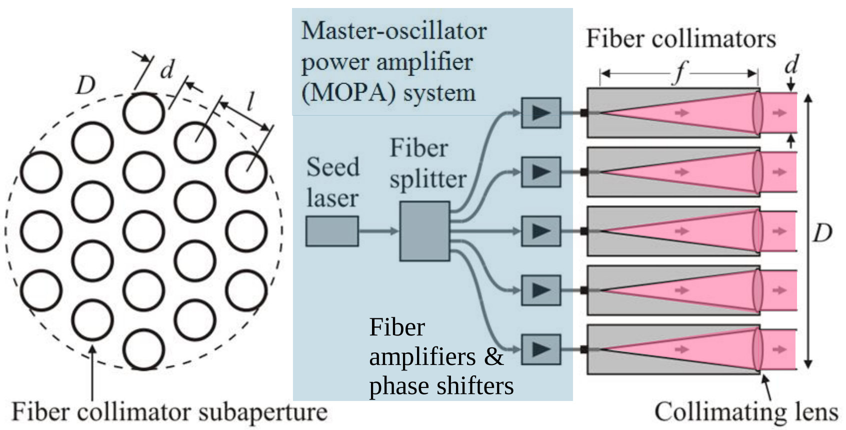
M. F. Spencer and T. J. Brennan, "Deep-turbulence phase compensation using tiled arrays", Optics Express, vol. 30, 19, (2022).

Conventional vs Coherent Fiber Array Based Laser Transmitter Systems: Pros & Cons

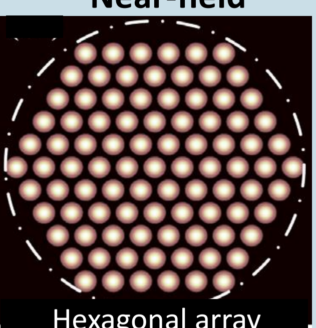
Conventional beam director



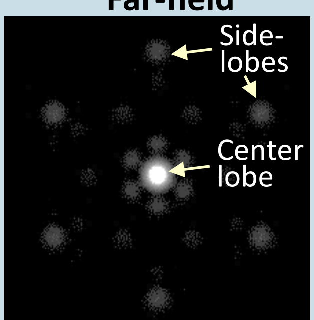
Fiber-collimator array-based beam director



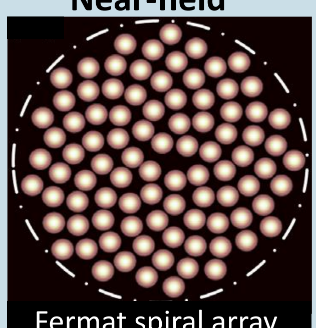
Near-field



Far-field

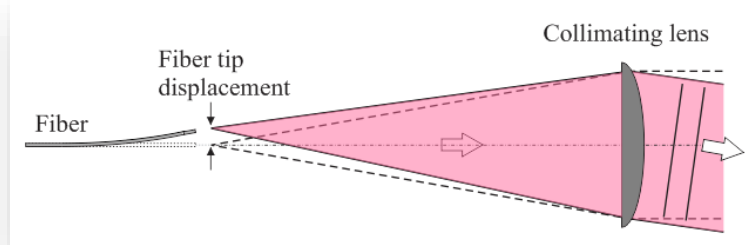


Near-field



Wei Li, et al, Optics Communications (2022)

Beam combining in fiber array laser transmitters

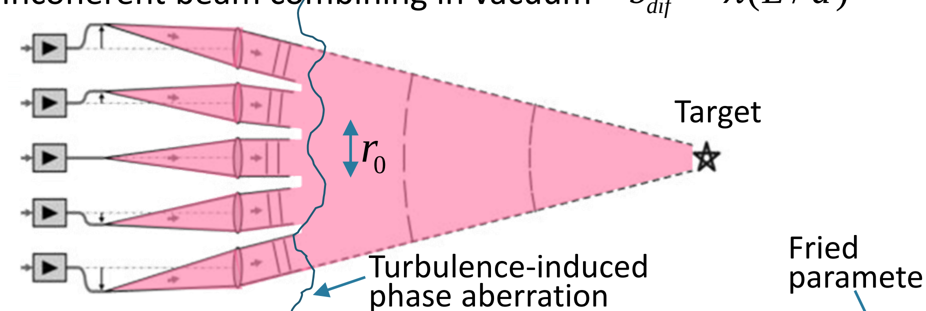


M. Vorontsov et al ; *IEEE Journal of Selected Topics in Quantum Electronics*, Vol. 15, No. 2, 269-280 (2009)

Combined beam spot size at the target plane

Coherent beam combining in vacuum $b_{dif} \simeq \lambda(L/D)$

Incoherent beam combining in vacuum $b_{dif} \simeq \lambda(L/d)$



Characteristic beam size in atmospheric turbulence without adaptive optics (AO): $b_{target} \simeq \lambda(L/r_0)$

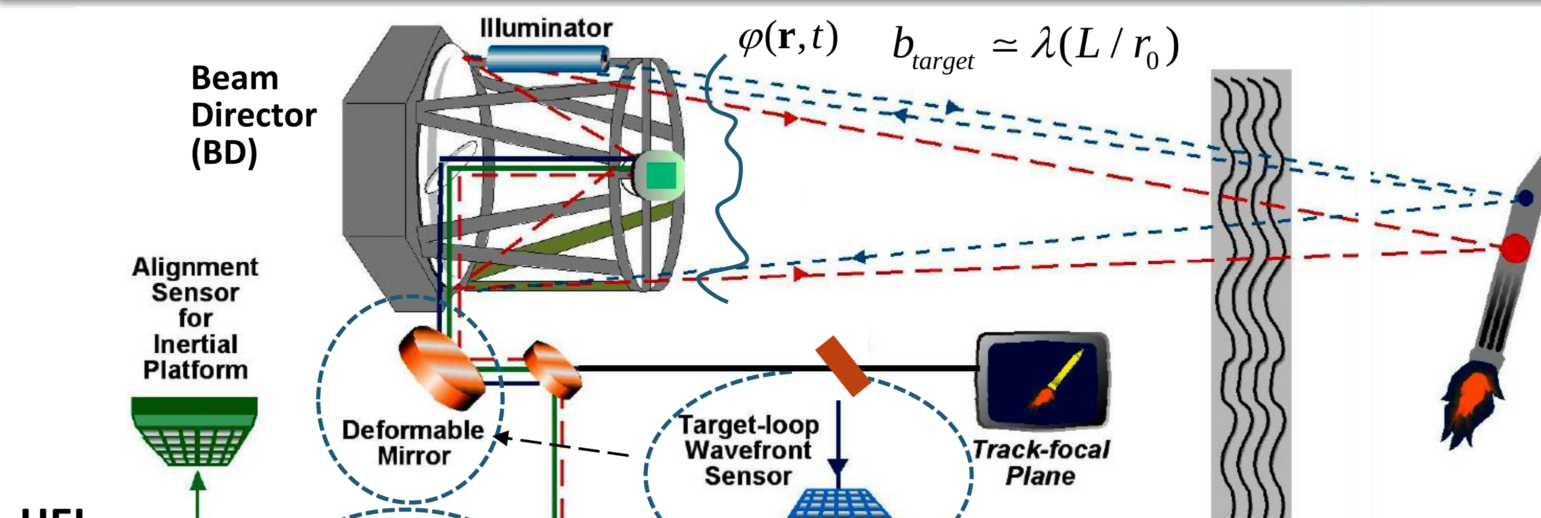
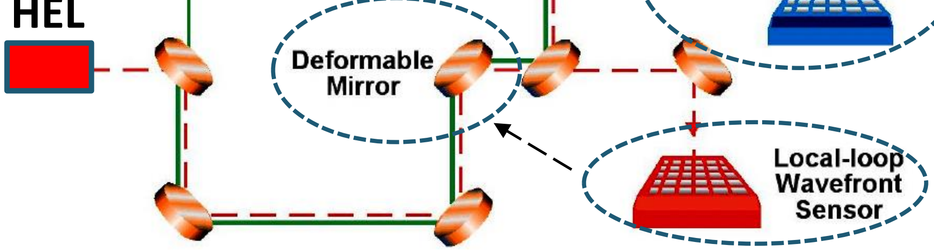
Cons:

- Energy losses in side lobes
- Requirement for individual beam pointing & mitigation of phase noise in fiber channels
- Nonlinear effects in fibers

Pros:

- Scalability
- Compactness
- High quality beam
- No beam train
- Extremely fast piston phase control

Conventional High Energy Laser (HEL) Beam Projection Systems with Phase-Conjugate Adaptive Optics (AO): Challenges

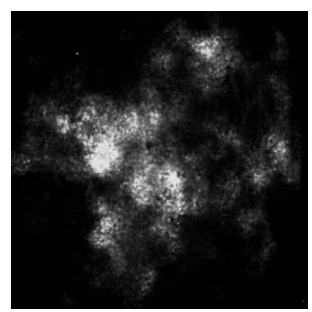
$b_{target} \simeq \lambda(L/r_0)$

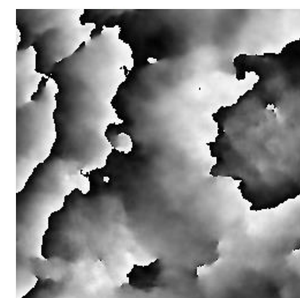
What to expect from an ideal phase-conjugate AO system?

$b_{dif} \simeq \lambda(L/D)$ **??**

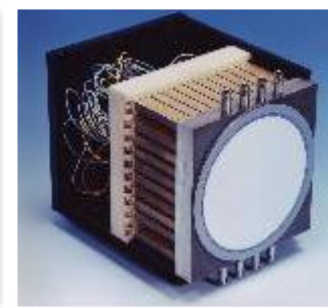
M.A. Vorontsov, et al., JOSA A, Vol. 24, (2007)

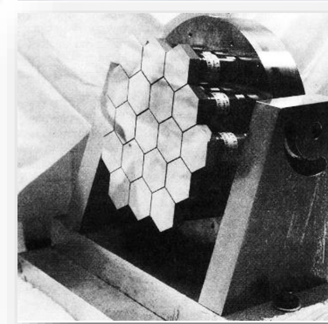
Target-return intensity and phase





Faceplate DM





Segmented DM
Hardy, 1998

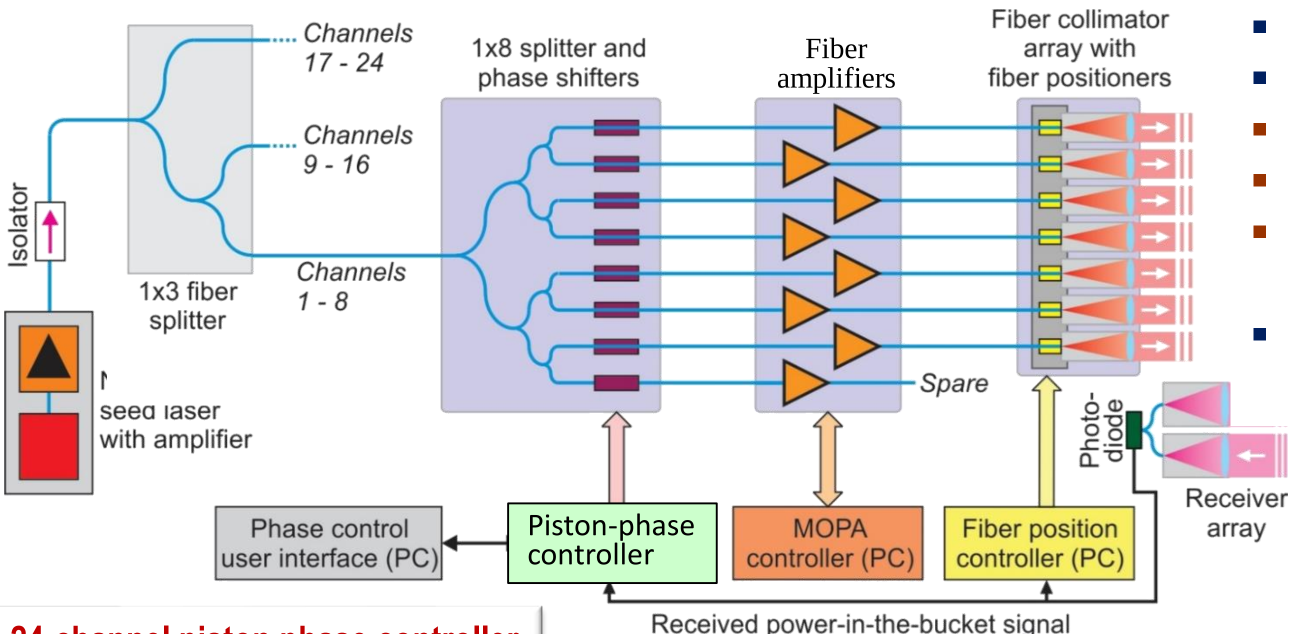
Technical Issues/ Challenges

- Complexity (4 wavelengths), weight, cost, reliability
- Beam quality, maintaining alignment, thermal management, platform jitter, etc.
- Need for two Adaptive Optic (AO) systems for HEL beam clean up & for atmosphere.
- Insufficiently fast AO due to deformable mirror (DM) bandwidth limitations
- Challenges of wavefront sensing in strong scintillations (deep turbulence): Rytov >0.3
- Thermal blooming, target speckles

G. P. Perram, S. J. Cusumano, R. L. Hengehold, and S. T. Fiorino "*Introduction to Laser Weapon Systems*" DEPS (2010)

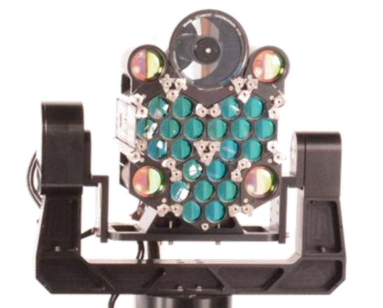
Coherent Fiber Array Laser Transceiver: Example of Low-Power System Implementation

Fiber-array based laser transmitter: major modules



Key advantages:

- High quality beam with $M^2 < 1.1$
- Single-wavelength operation
- No beam optical train
- No wavefront phase sensing
- No DMs: piston phase control with up to GHz bandwidth
- Stair-mode beam pointing & steering



https://www.iiviad.com

24-channel piston phase controller with integrated phase shifters

- 500 kHz iteration rate
- Accounts for propagation delay time
- Adaptive gain and perturbation amplitude

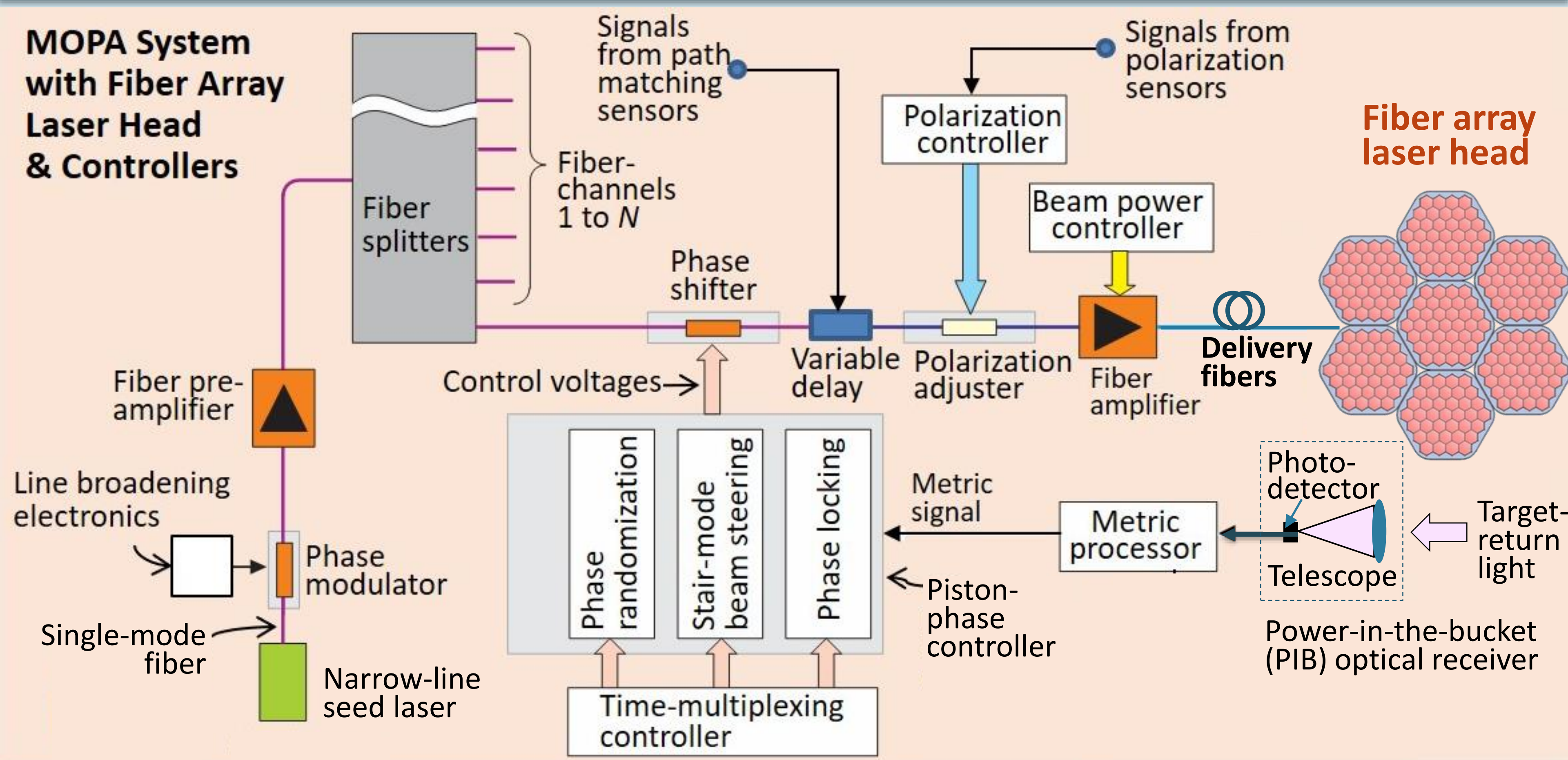
24-channel fiber system with fiber amplifiers

- 0.25 W per channel
- Output power control

Fiber-integrated 1x8 splitter & phase shifter

M. Vorontsov and T. Weyrauch, Appl. Opt., Vol. 55, No. 35, 9950 (2016).

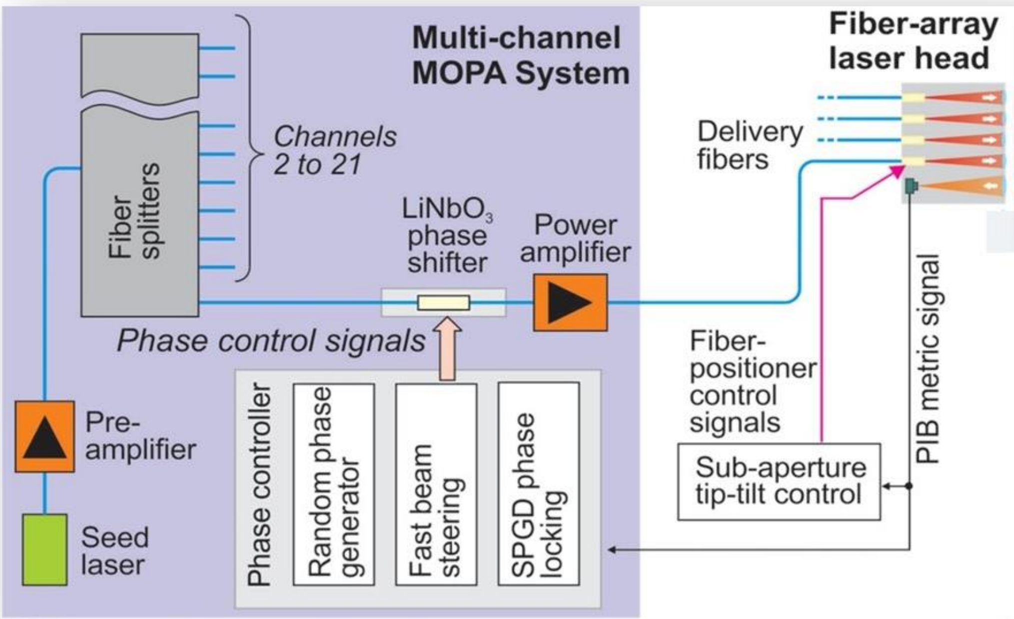
High-Power Multi-Channel Coherent Fiber Array: System Architecture



Major modules of a notional high-power coherent fiber array laser system

Low-power MOPA	Fiber-array laser head	Piston-phase controller	Polarization controller	PIB metric processor
High-power amplifiers	Tip/Tilt controller	Path-matching controller	Optical receiver (PIB)	Tracking system

Target-in-the-Loop (TIL) Coherent Beam Combining (CBC) with Stochastic Parallel Gradient Descent (SPGD) Control



Delayed-feedback SPGD control with adaptive gain and perturbation amplitudes

Piston phase control signals update at *n*th SPGD iteration

$$u_j^{(n+1)} = u_j^{(n)} + \gamma^{(n)} \left[J_+^{(n)} - J_-^{(n)} \right] \delta u_j^{(n-\Delta n)}$$

$\delta u_j^{(n)} = \alpha^{(n)} \zeta_j^{(n)}$ control signals perturbations

$\zeta_j^{(n)}$ random numbers with uniform probability distribution inside the interval [-1,1]

$J_+^{(n)}$, $J_-^{(n)}$ ⇨ Metric values corresponding to positive (+) and negative (-) control signals perturbation

$\delta u_j^{(n-\Delta n)}$ Perturbations applied Δn iterations before *n*th iteration

Alternative TIL CBC approaches:
Multi-dithering (O'Meara, JOSA, 1977); LOCSET (Shay, Opt. Express, 2006)
B. Rouze et al, Appl. Optics, v. 60, 27, (2021)

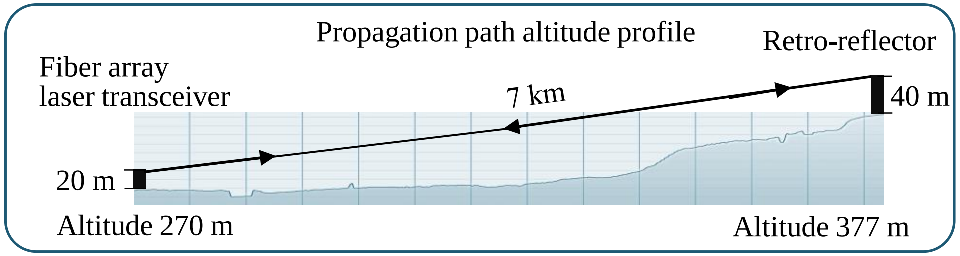
CBC control algorithms	Related publications
SPGD control algorithm	M. Vorontsov, G. W. Carhart, and J.C. Ricklin, "Adaptive phase-distortion correction based on parallel gradient-descent optimization," *Opt. Lett.* Vol. 22, No.12 , 907-909, (1997).
SPGD with adaptive perturbations	M. Vorontsov, and V. P. Sivokon, "Stochastic parallel gradient descent technique for high-resolution wavefront phase distortion correction," *JOSA A*, Vol. 15, No. 10, 2745-2758 (1998).
Decoupled (vector) SPGD	M. Vorontsov, "Decoupled stochastic gradient descent optimization for adaptive optics: integrated approach for wave-front sensor information fusion," *JOSA A* , Vol. 19, No 2, Feb. 356-368, (2002).
Delayed-feedback SPGD	T. Weyrauch, M. Vorontsov, et al "Experimental demonstration of coherent beam combining over 7 km propagation path," Optics Letters, 15, (2011)
Speckle-metric based SPGD for CBC on non-cooperative speckle targets	M. Vorontsov, T. Weyrauch, S.L. Lachinova, M. Gatz, and G. W. Carhart "Speckle-metric-optimization-based adaptive optics for laser beam projection and coherent beam combining, " Optics Letters, 15, V. 37, N. 14, 2802-2804 (2012) M. A. Vorontsov "Speckle effects in target-in-the-loop laser beam projection systems," Adv. Opt. Techn. 2(5-6): 369–396 (2013) M. A. Vorontsov and T. Weyrauch," High-power lasers for directed-energy applications: comment," Appl. Optics, 55, No. 35, December 10, 9950-9953 (2016).

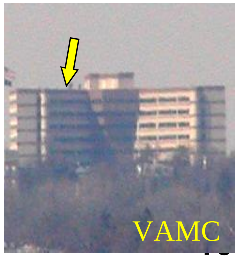
Coherent Combining of 21 Beams at a Retro-Target over 7 km with Delayed-SPGD Controller: Experimental Setting

Instrumentation installation on VAMC roof

Available sensor data:
Wind speed, temperature, humidity, pressure
C_n^2, Fried parameter, Rytov number, scintillation index (at UD site only)

University of Dayton 7 km Atmospheric Propagation Testbed

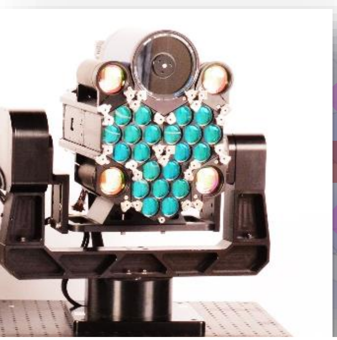


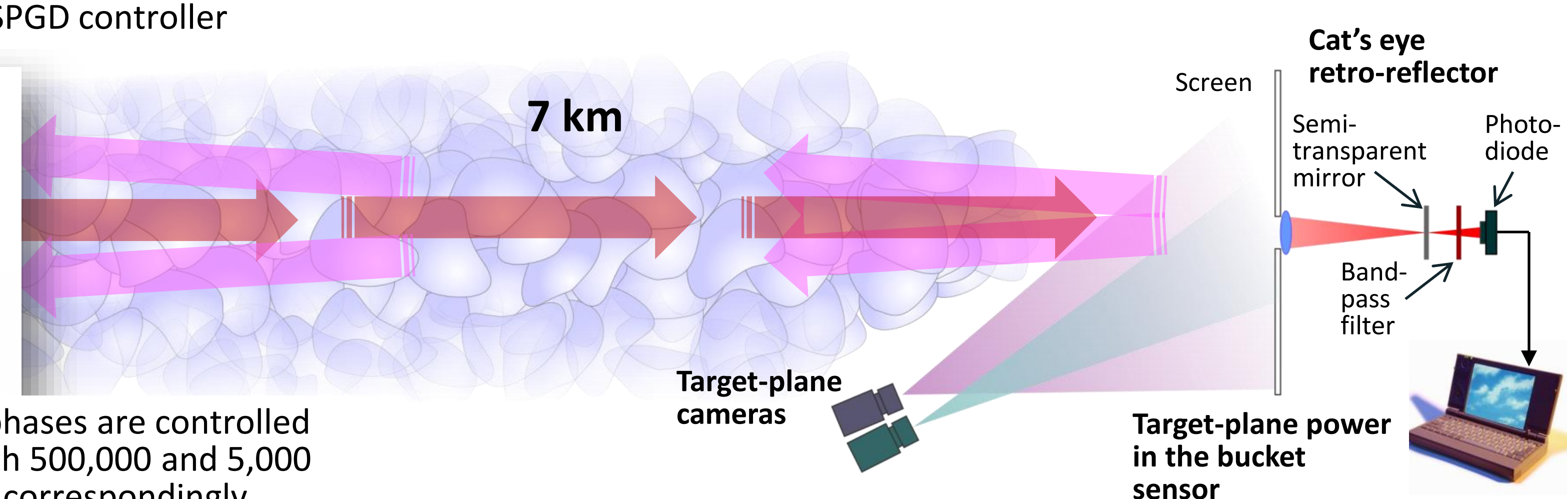


Coherent Combining of 21 Beams at a Retro-Target over 7 km with Delayed-SPGD Controller: Experimental Setting

AO control of piston phases and wavefront tip and tilt aberrations at 21 fiber array subapertures

Experiments were performed with delayed-feedback SPGD controller



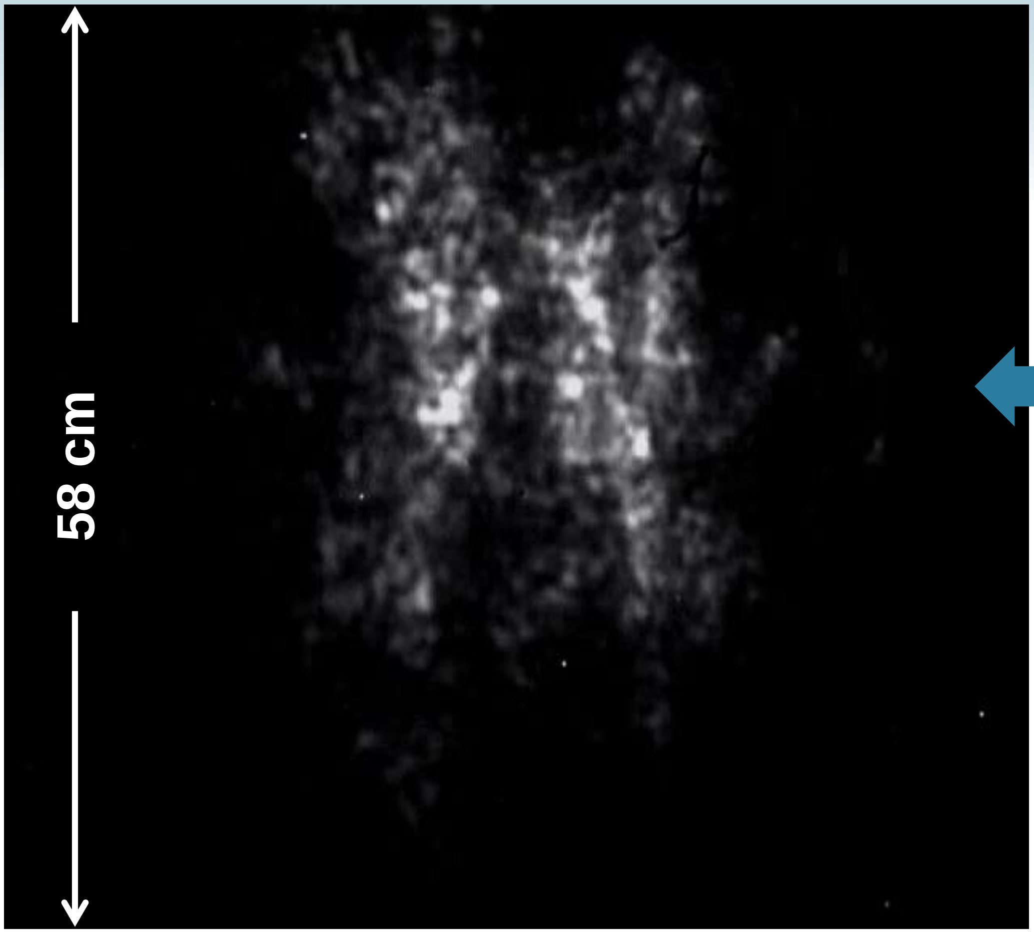


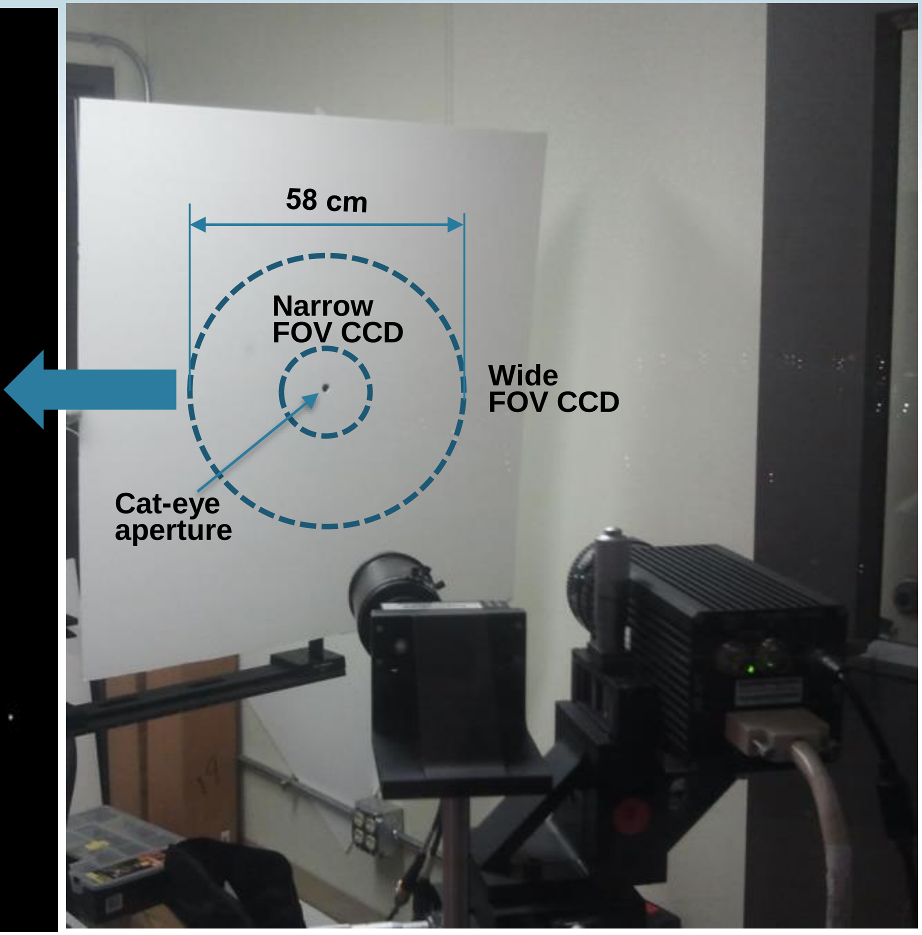
Piston and tip/tilt phases are controlled asynchronously with 500,000 and 5,000 SPGD iteration/sec correspondingly.

Coherent Combining of 21 Beams at a Retro-Target over 7 km with Delayed-SPGD Controller

Atmospheric conditions: $\langle C_n^2 \rangle = 1.6 \times 10^{-15}\ \mathrm{m}^{-2/3}$ **Rytov number** $\langle \sigma_R^2 \rangle = 0.4$

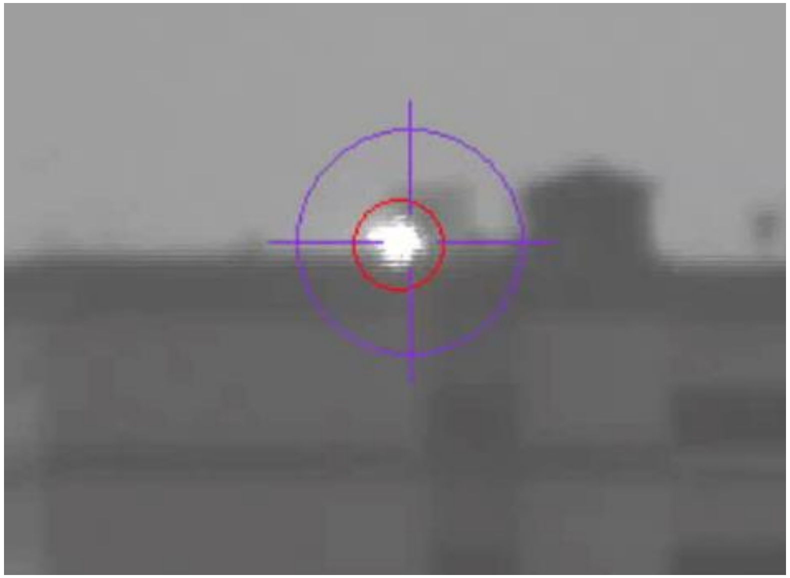
Rytov number (log-amplitude variance for plane wave) $\sigma_R^2 = 0.307 k^{7/6} L^{11/6} C_n^2$



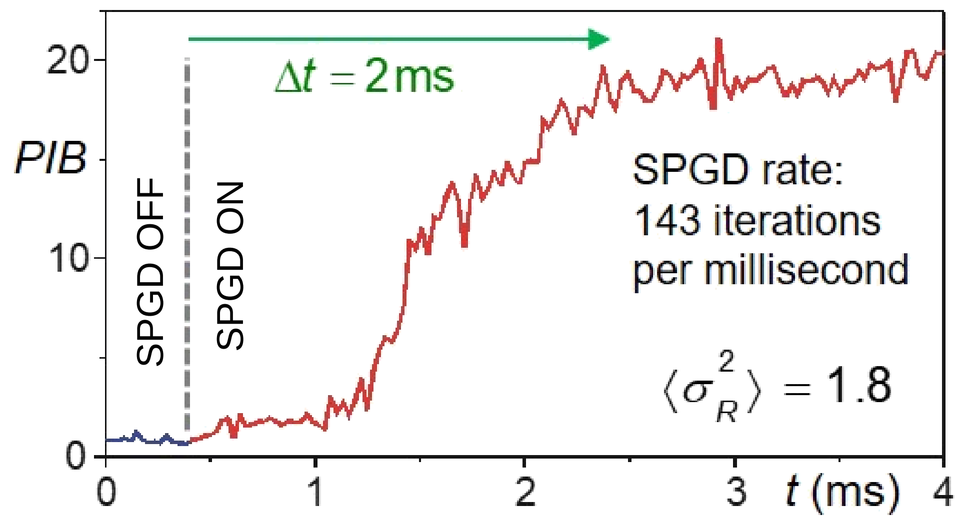


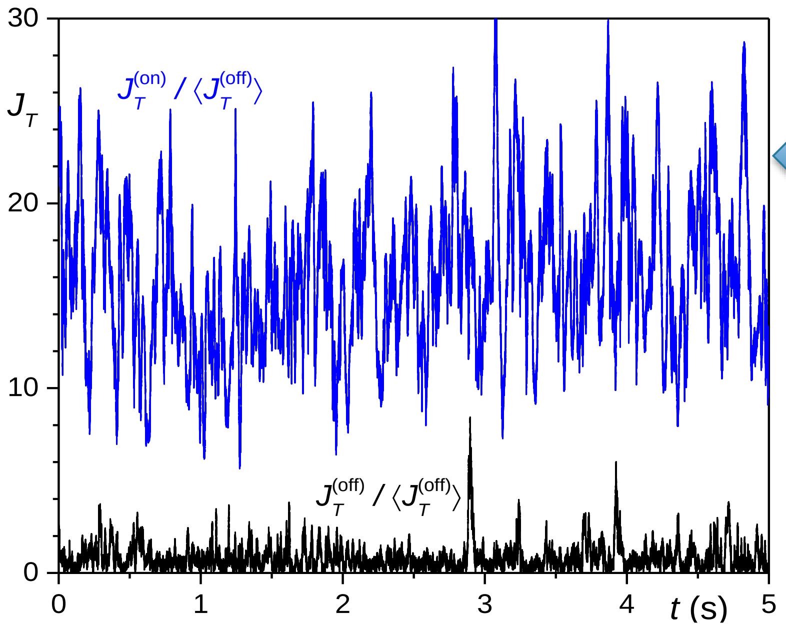
21-channel SPGD phase-locking controller OFF and ON (tip/tilt controller is OFF)

Coherent Combining of 21 Beams at Moving Retro-Target over 7 km with Delayed-SPGD Control



Characteristic PIB metric time evolution curve



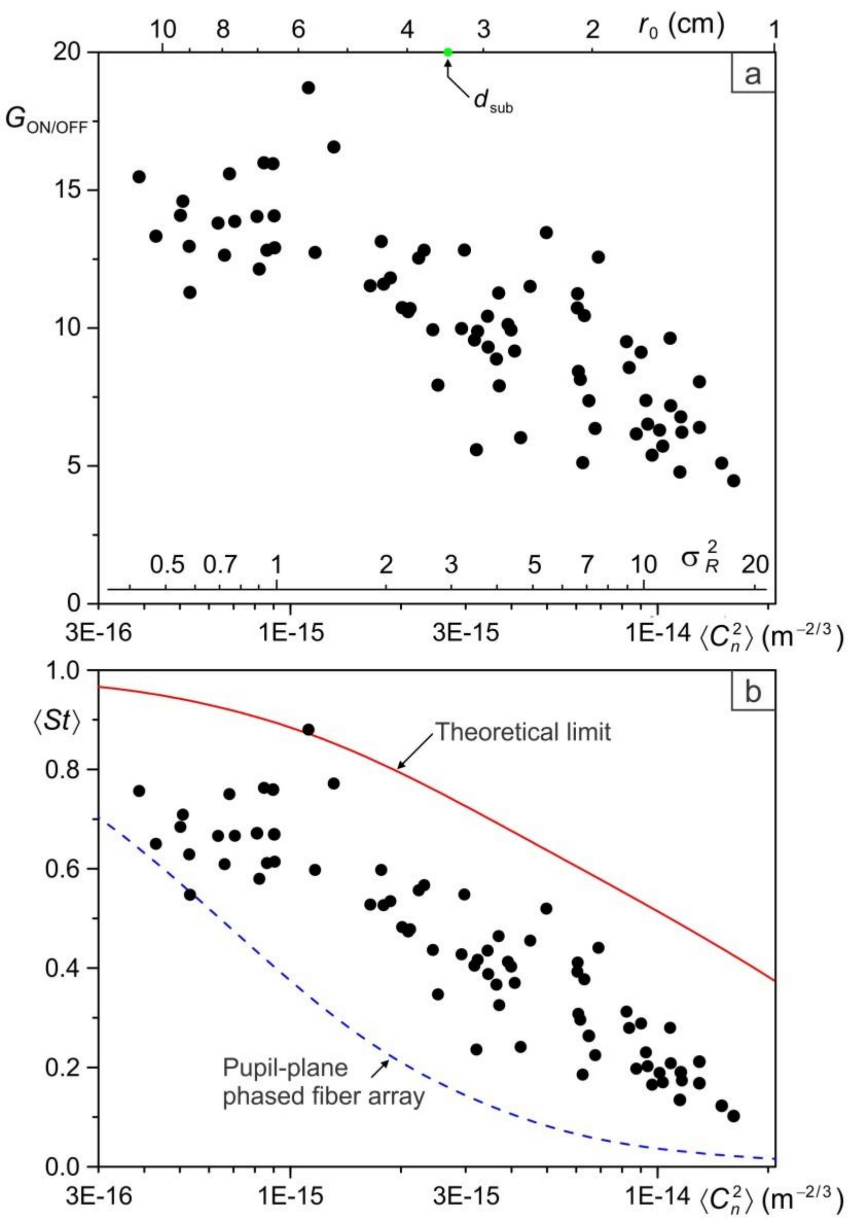


First five seconds of the target plane power-in-the-bucket (PIB) signals without and with TIL SPGD control of beamlet piston phases. Both signals are normalized to the average of the control-off state.

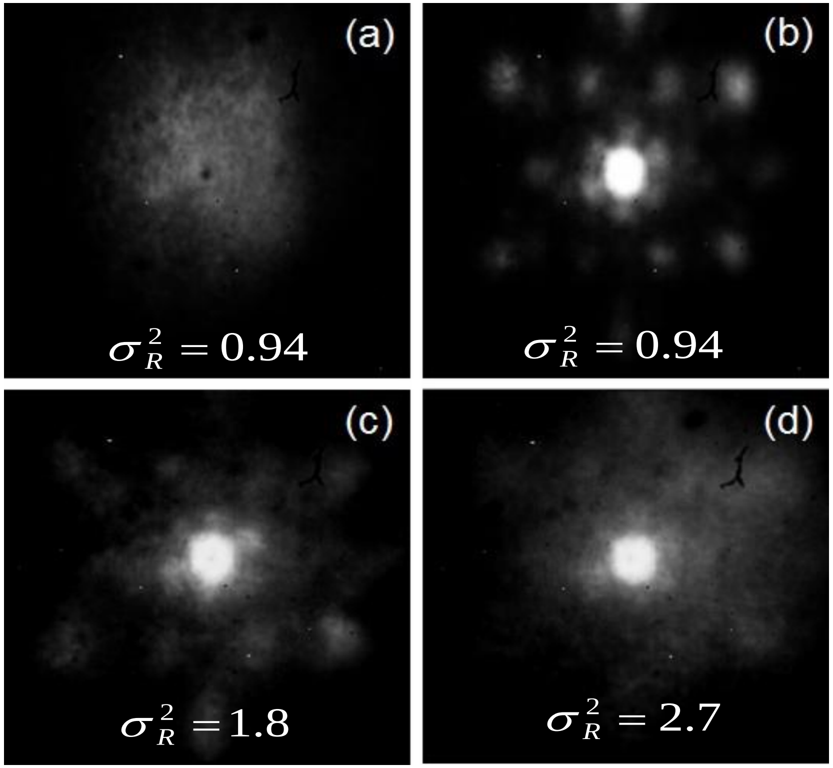
M. Vorontsov, T. Weyrauch, S. Lachinova, T. Ryan, A. Deck, M. Gatz, V. Paramonov, and G. Carhart, “Coherent beam combining and atmospheric compensation with adaptive fiber array systems,” in Coherent Laser Beam Combining, A. Brignon, ed. (Wiley-VCH, Weinheim, 2013), chap. 6.

M.A. Vorontsov, G. Filimonov, V. Ovchinnikov, E. Polnau, S.L Lachinova, T. Weyrauch, and J. Mangano, “Comparative efficiency analysis of fiber-array and conventional beam director systems in volume turbulence,” Applied Optics, V. 55, N. 15, May 20, 4170-4185 (2016).

Efficiency of Turbulence Effects Mitigation via Coherent Combining of 21 Beams at a Retro-Target (7 km): Summary



Experimental results (dots) for the gain factor Gin (a) and the Strehl ratio St (b) obtained during multiple target-in-the-loop phase locking trials over 7 km, under different atmospheric turbulence conditions with the fiber-array system composed of 21 subapertures

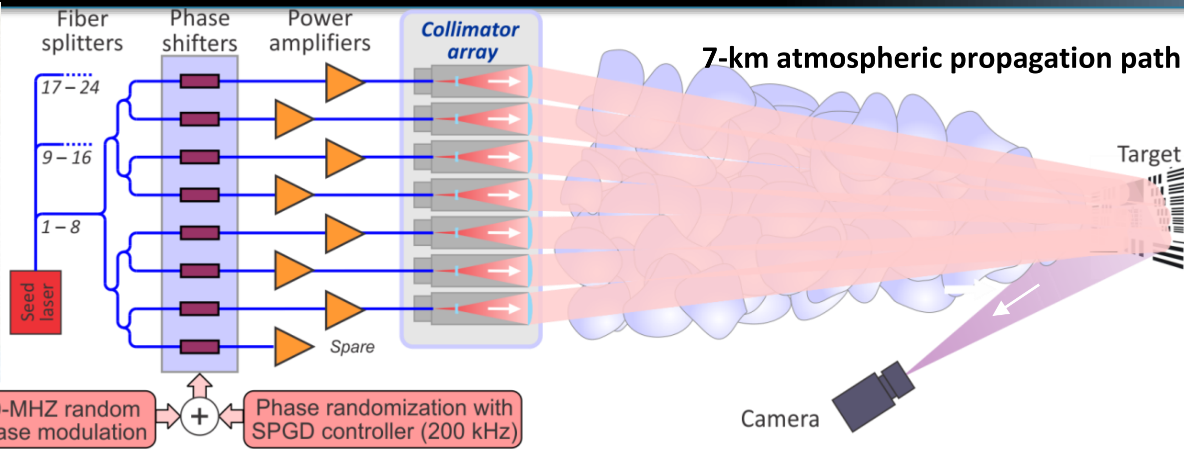


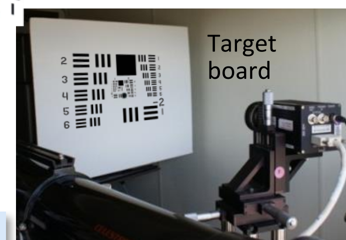
Atmospheric-averaged irradiance distributions on the target-plane screen (58 × 58 cm² area) as seen by the target-plane camera with SPGD phase control off (a) and on (b, c, d)

T. Weyrauch, M. Vorontsov, et al *Optics Letters*, Vol. 41, No. 4, 840-843 (2016).

Laser Beams with Controllable Coherence & "Speckle-Free" Active Imaging with Fiber-Array- Based Target Illumination

Fiber array-based laser illuminator

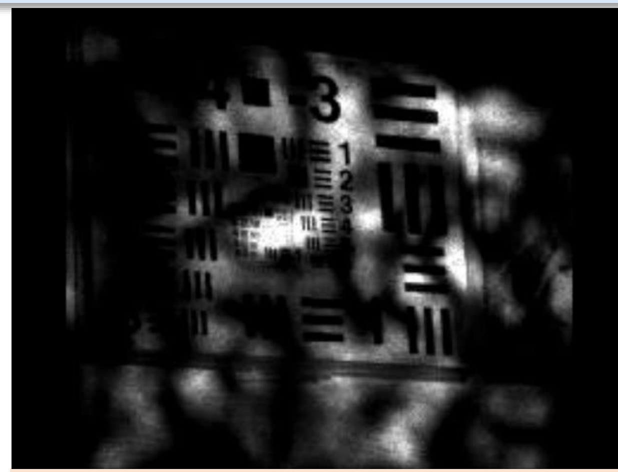




Side-by-side comparison of target image quality with a conventional laser illuminator using a Cassegrain telescope and fiber-array system with 21-subapertures and randomized piston phases

$$C_n^2 = 1.8 \times 10^{-15}\ \mathrm{m}^{-2/3}$$

Short-exposure image obtained with target illumination by conventional (Cassegrain telescope) beam director



Short-exposure image obtained with target illumination by fiber array-based beam director (incoherent combining)

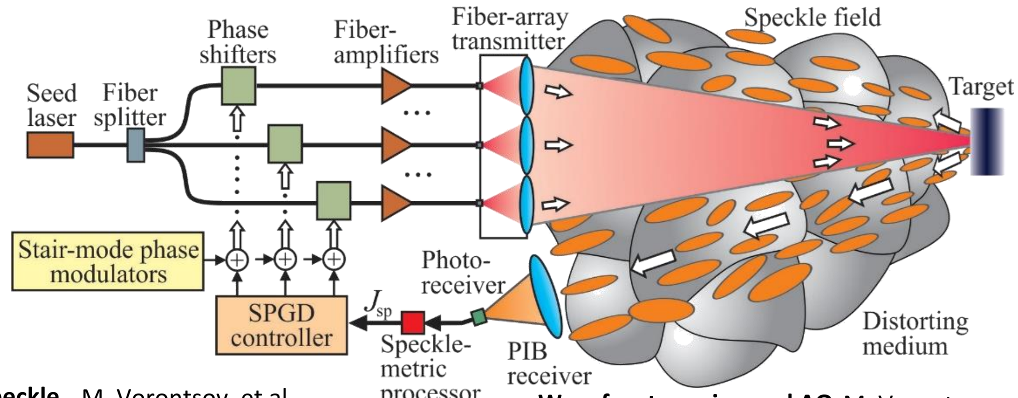
Short-exposure image obtained with target illumination by fiber array using randomized piston phases

Applications: Active imaging (space object identification), directed energy (speckle-free wavefront sensing)

M. A. Vorontsov and T. Weyrauch, "Laser Beam Engineering and Atmospheric Turbulence Effects Mitigation with Coherent Fiber Array Systems," in *Propagation Through and Characterization of Atmospheric and Oceanic Phenomena*, OSA Technical Digest (Optica Publishing Group, 2016), paper Tu2A.1.

High-Speed Stair-Mode Beam Pointing & Steering with Coherent Fiber-Array Beam Director

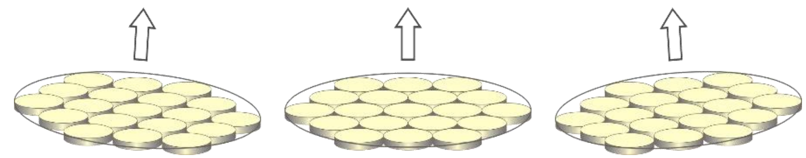
Laser beam projection on an extended target



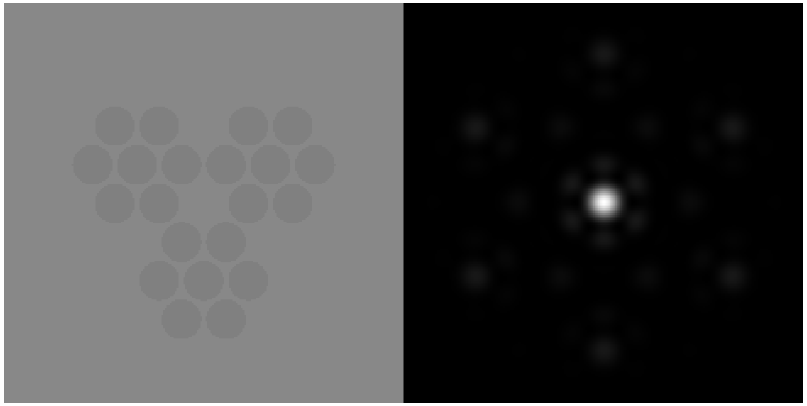
Speckle metrics M. Vorontsov, et al, Opt. Let, V. 37, N. 14, (2012)

Wavefront sensing and AO with Collett-Wolf beacon M. Vorontsov, et al, Appl. Optics (2019)

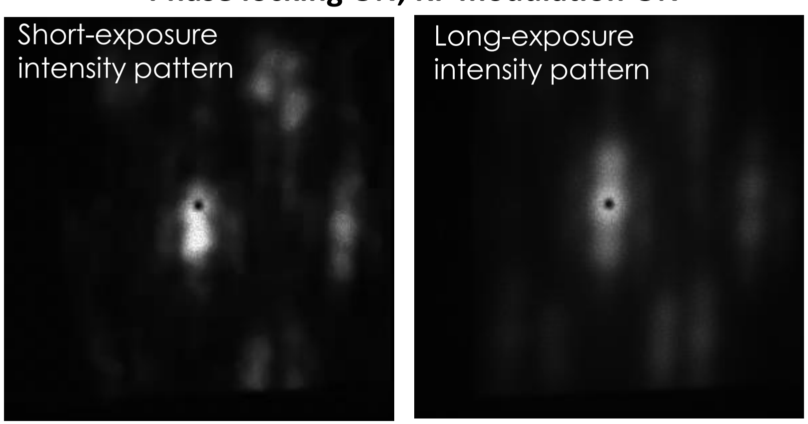
Beam scanning creates an incoherent (Collett-Wolf) beacon at the target, which can be used for speckle-free wavefront sensing and speckle-metric-based coherent beam combining



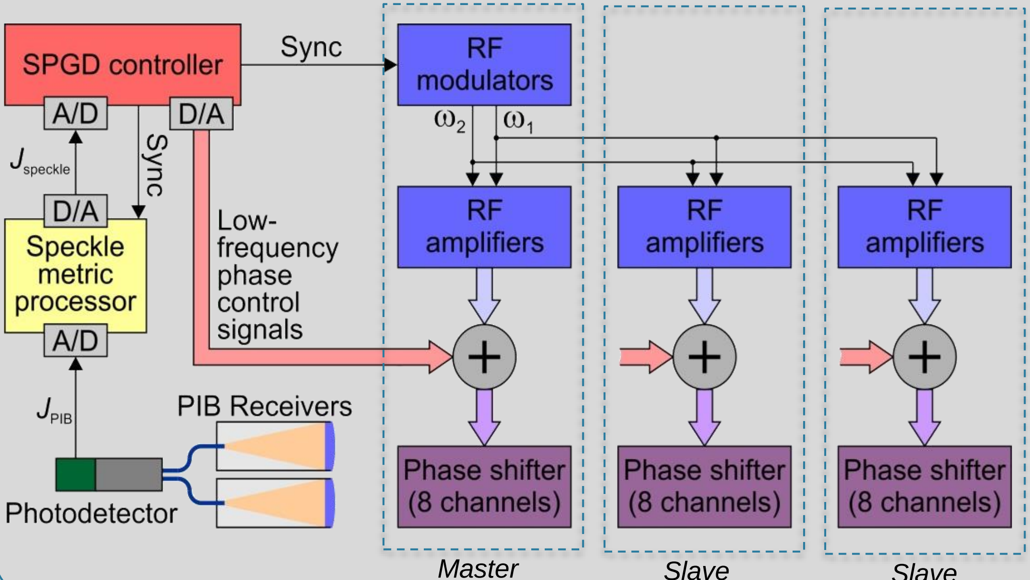
Generation of global tilts through local piston phase control of the beams transmitted by the fiber array



Phase locking ON, RF modulation ON



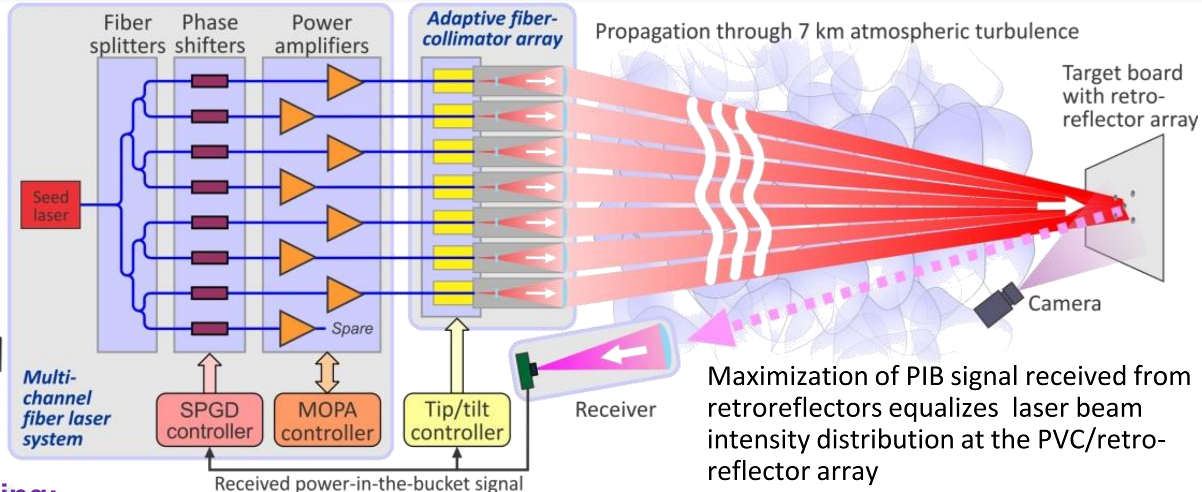
2D hit-spot position modulation (stair-mode beam steering) for generation of an incoherent (Collett-Wolf) beacon at an extended target using an adaptive fiber array laser illuminator



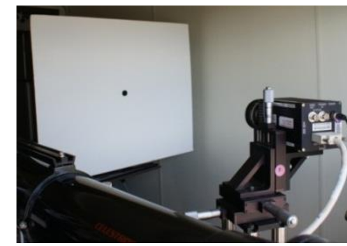
M. A. Vorontsov and T. Weyrauch, "Laser Beam Engineering and Atmospheric Turbulence Effects Mitigation with Coherent Fiber Array Systems," in *Propagation Through and Characterization of Atmospheric and Oceanic Phenomena*, OSA Technical Digest (Optica Publishing Group, 2016), paper Tu2A.1.

Remote Power Beaming with Coherent Fiber Array-Based Adaptive Beam Shaping

Fiber array-based laser illuminator



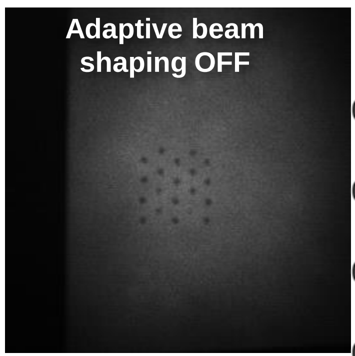
Maximization of PIB signal received from retroreflectors equalizes laser beam intensity distribution at the PVC/retro-reflector array

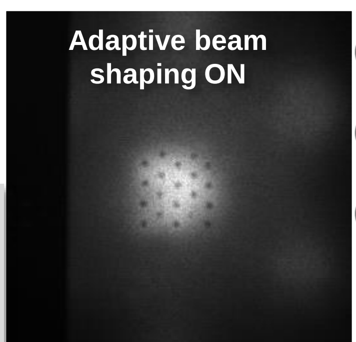


Remote power beaming: challenges

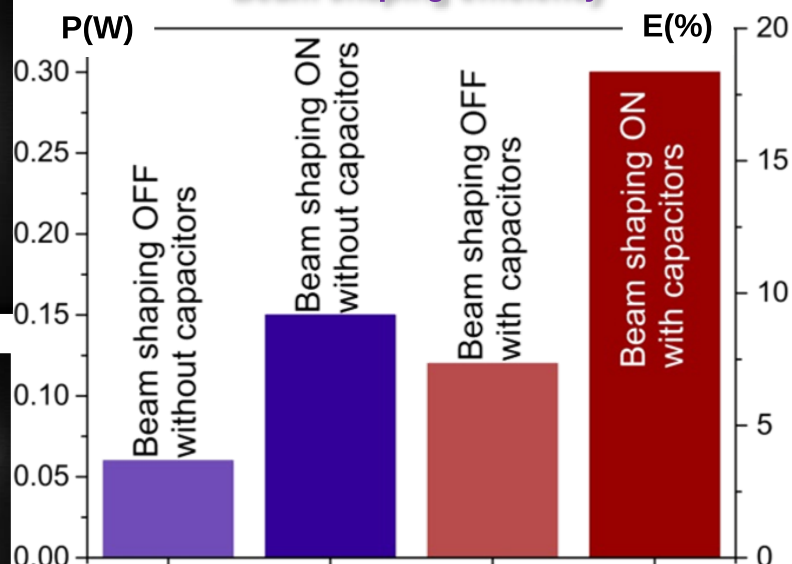
- Power losses due to mismatch between the PV array and projected laser beam footprint caused by tracking errors, and turbulence-induced beam wander and widening
- Spatial inhomogeneity of the intensity distribution at the PV array
- Turbulence-induced large amplitude (giant) laser beam intensity spikes that can damage PV cells

AO beam shaping leads to maximization of both the overall laser power inside the PV cell assembly and its spatial uniformity.

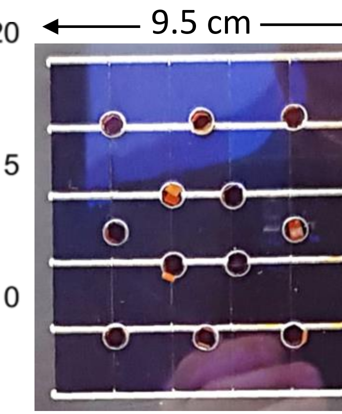




Beam shaping efficiency



Integration of capacitors to each PV cell allows partial mitigation of turbulence-induced scintillations

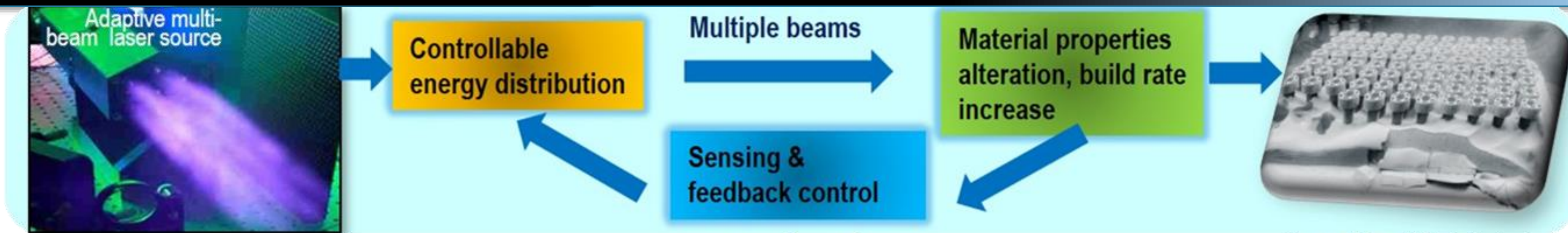


Laser power converter assembly optimized for λ = 1064 nm

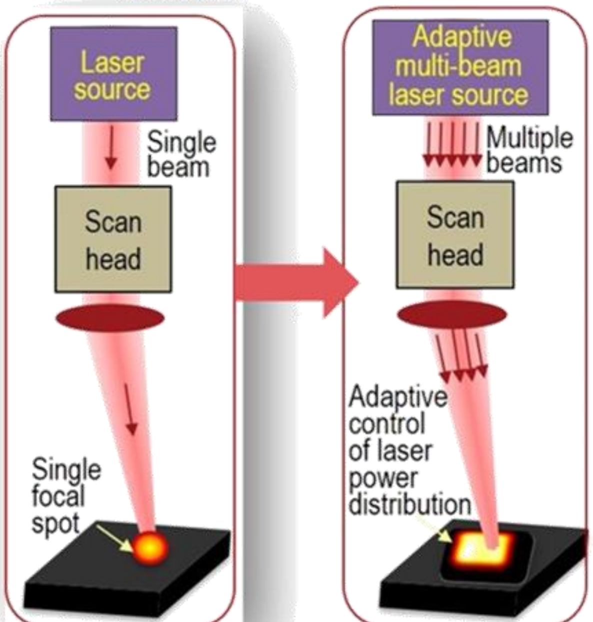
C. Niu, B. Bordbar, and M. Vorontsov; Proc. SPIE 10744, Laser Beam Shaping XVIII, 107440P (2018);

M. Vorontsov, T. Weyrauch, D. Bricker, Y. Masui, T. Tumolillo, B. Bordbar, E. Conrad; "Remote Power Beaming with Adaptive Fiber-Array Laser Sources", DEPS Symposium, Destin FL (2019)

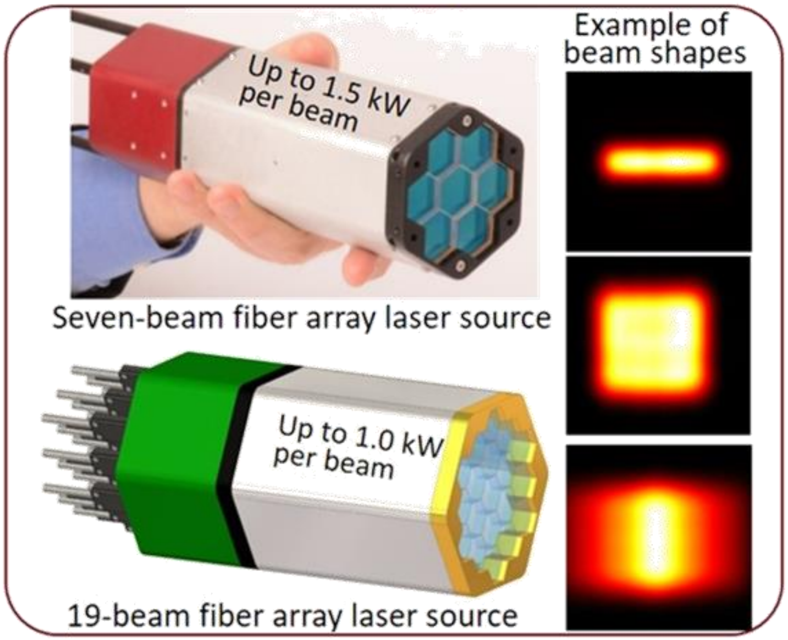
Laser Material Processing & Additive Manufacturing with Adaptive Fiber Array Laser Power Sources



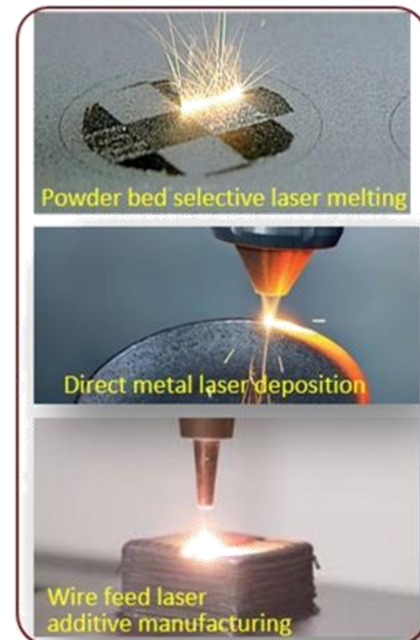
How it is different

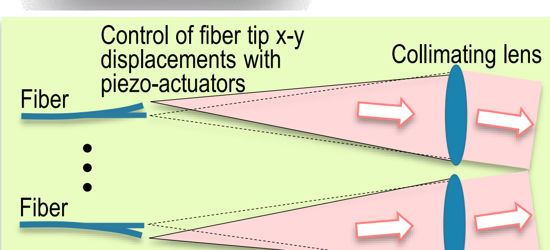


Technology

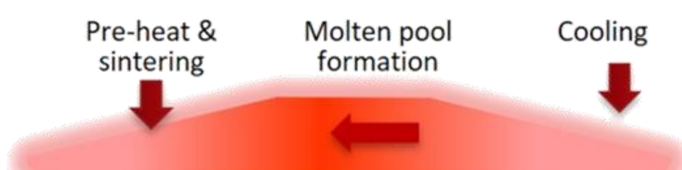


Applications





Beam pointing control concept

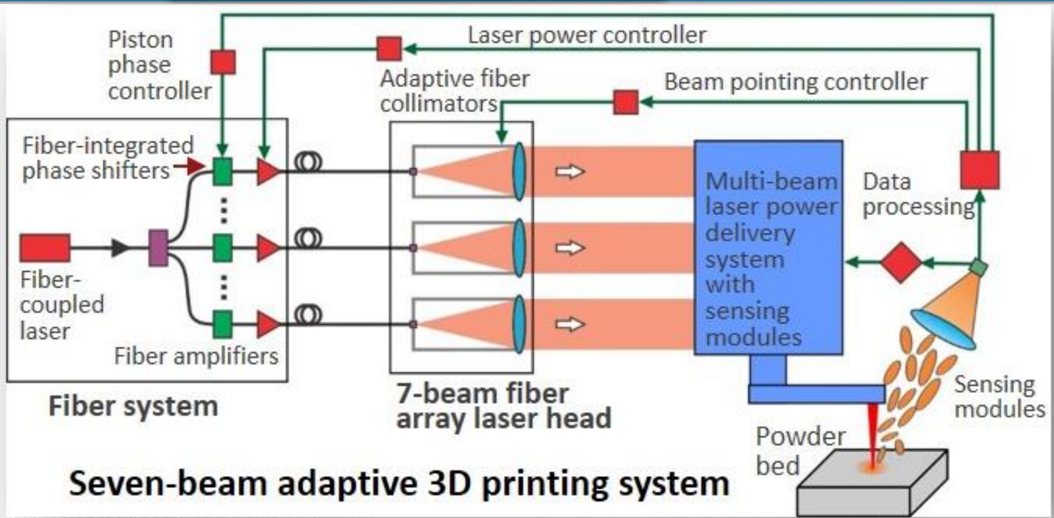


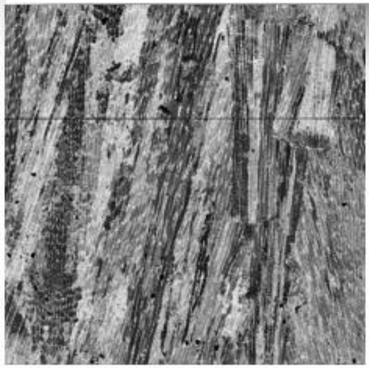
in-situ control of thermal gradients during laser material processing and additive manufacturing

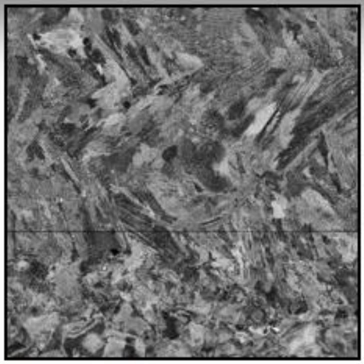
M. Vorontsov, N. Farwell & M. Massey "Adaptive Multi-Beam Laser Additive Manufacturing (AMB-LAM) Technology: Instrumentation, Process Development & Demonstration", Materials Science & Technology Technical Symposium, Nov. 2-6, 2020

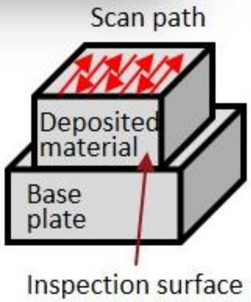
M. Vorontsov, "Additive manufacturing in metals with a fiber array laser source and adaptive multi-beam shaping" Patent number: 11267074; March 8, 2022

Laser Material Processing & Additive Manufacturing with Adaptive Fiber Array Laser Power Sources





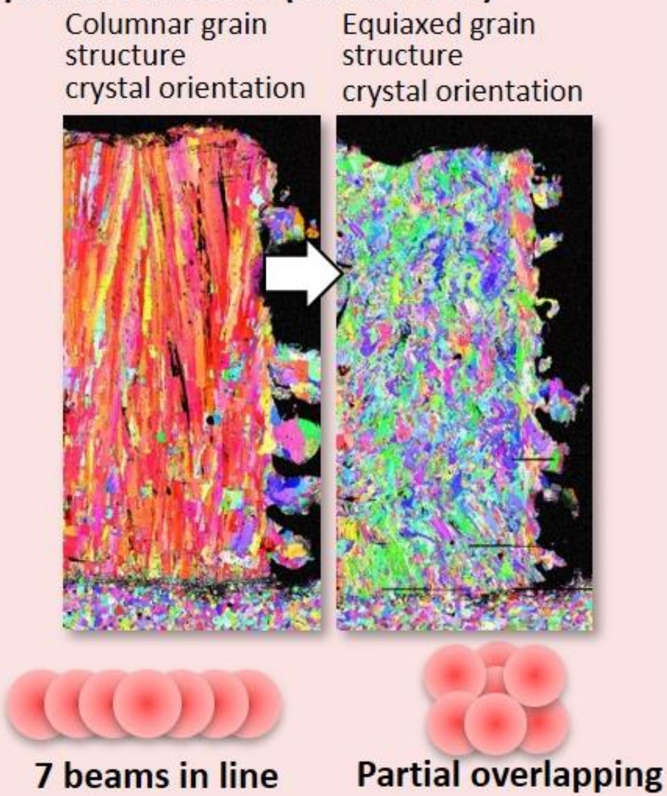




- Microstructure growth in build thickness direction
- Columnar grain structure
- Modified grain structure due to different cooling rates

- Randomly oriented microstructure growth alternating between build layers
- Random crystal grain structure confirmed by EBSD measurement

Demonstration of columnar equiaxed transition with control of the laser power spatial distribution at the powder material (Inconel 718)



The EBSD characterization was performed by MRL and Sandia National Labs.

The developed adaptive 7-beam powder bed SLM system was utilized for printing basic coupons using different beam shapes from the following materials: Inconel 718, 7075Al, Ti-6Al-4V, 316L stainless steel and Ti-48Al-2Cr-2Nb. The coupon characterization demonstrated the potential for significant improvements in such characteristics as surface finish, density, tensile yield, ductility and micro-crack mitigation.

M. Vorontsov, N. Farwell & M. Massey "Adaptive Multi-Beam Laser Additive Manufacturing (AMB-LAM) Technology: Instrumentation, Process Development & Demonstration", Materials Science & Technology Technical Symposium, Nov. 2-6, 2020

Concluding Remarks

Coherent fiber array laser technology: emerging applications

Applications	Total power	Power / beam
Directed Energy	20 kW- 100 kW	1.0 kW- 1.5 kW
Material Processing	2 kW- 20 kW	0.1 kW- 1.0 kW
Power Beaming	1.5 kW – 3.0 kW	0.1 kW- 0.3 kW
Laser Additive Manufacturing	0.7 kW – 2.0 kW	0.1 kW
Laser Communications	1.0 W – 50 W	0.1 W

Coherent fiber-array-based laser beam directors offer unique opportunities for:

- Adaptive compensation of turbulence and aero-optics effects for directed energy
- Engineering of a variety of laser beams with controllable spatio-temporal distributions of phase and polarization
- Dynamic control of laser beam coherence in time and across the beam aperture
- Mitigation of speckle effects for wavefront sensing and speckle-free active imaging
- Mitigation of intensity scintillations and adaptive beam shaping for optical power beaming applications
- Beam shaping for laser material processing and additive manufacturing