Analysis and Experimental Demonstration of a Conformal Adaptive Phase-locked Fiber Array for Laser Communications and Beam Projection Applications

Ling Liu, Mikhail Vorontsov (Ph.D. Advisor)

The Institute for Systems Research

Intelligent Optics Lab (http://www.iol.umd.edu/)

1. Introduction

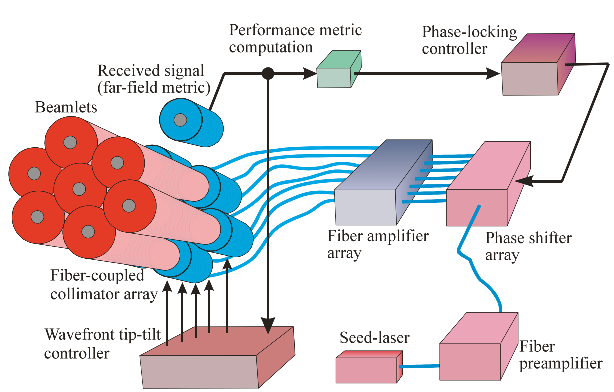
Shortcomings of existing monolithic large-aperture beam forming telescopes in free-space laser communications and beam projection applications, which are usually heavy, bulky and expensive, stimulate development of compact, light, less expensive, power-scalable and element-failure tolerant system composed of multiple identical phased subaperture telescope elements.

The multiple beams from subapertures experience wavefront phase distortions when propagating through atmospheric turbulence to the far field. System performance such as far-field beam divergence angle and target focal spot size is degraded unless adaptive optics (AO) compensation is applied. Analysis shows that system performance with AO compensation is determined by Fried parameter r_o, a measure of atmospheric turbulence-induced phase distortion strength, and is independent of subaperture diameter d, if $d > r_o$. Phase-locking control is required for coherent beam combining at far-field receiver or target plane and smaller d is preferred for better performance. Residual phase error analysis shows that up to thousands of subapertures are needed for full compensation of atmospheric effects with relatively small Fried parameter r_o if only phase-locking (piston) control is used. When on-subaperture adaptive optics (AO) compensation for low-order wavefront Zernike aberrations due to atmospheric turbulence is used, total number of subapertures can be much smaller and control system can be much simpler with less control variables. The system with both phase-locking control and on-subaperture AO compensation is referred to as conformal adaptive phase-locked fiber array.

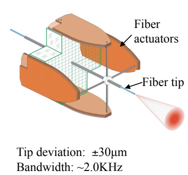
Analysis also shows that, with full compensation for wavefront phase distortions, conformal adaptive phase-locked fiber array with Gaussian beam profiles can behave like monolithic aperture system with equivalent aperture defined as the smallest circle enclosing all subapertures and same beam profile except that target plane peak intensity is reduced by conformal fill factor defined as the ratio of total subaperture areas over area of equivalent aperture circle. Far-field beam divergence angle and target focal spot size are roughly identical.

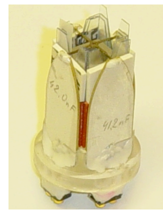
According to our knowledge, this is the first experimental demonstration of coherent beam combining with both phase-locking control and local on-subaperture AO compensation. So far, subaperture wavefront tip-tilt control has been implemented in our system.

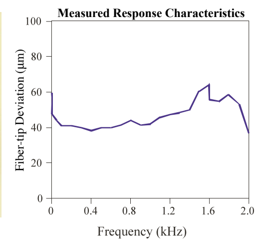
2. System Architecture and Key Subsystems

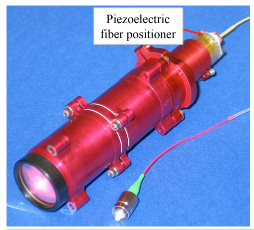


2.1. Conformal optical transmitter with subaperture wavefront tip-tilt compensation through piezoelectric fiber positioners

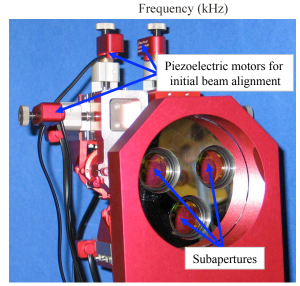




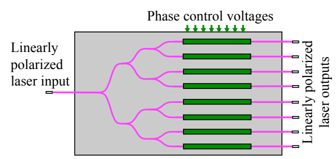


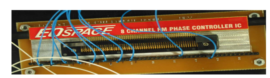


Subaperture lens diameter: **25 mm**
Focal length: **107 mm** (wavelength: **1064 nm**)

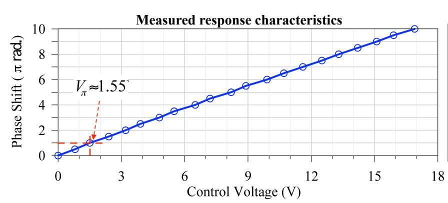


2.2. Multi-Channel LiNbO3 Polarization Maintaining Phase Shifter Array





Freq. modulation range: DC~1.0GHz
Phase shift dynamic range: ±10π radians
Polarization extinction ratio: > 25 dB
Halfwave voltage Vπ = 1.55V



Each phase shifter has roughly linear voltage-phase response characteristics:

$$\Delta\Phi(V) \approx V\frac{\pi}{V_\pi}$$

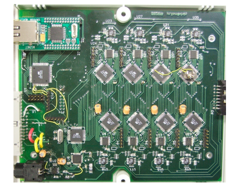
2.3. Phase-locking and subaperture wavefront tip-tilt feedback control systems

Feedback signal for control systems: $J = J(u_1, \dots, u_N)$, where $\{u_i\}$: control voltages can be obtained from far-field receiver or target through:

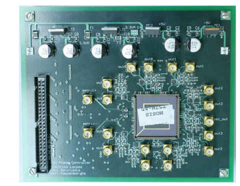
- radio frequency (RF) signal or counter propagating receiving optical beam for cooperative target (receiver in laser communication system)
- distributed power-in-the-bucket (PIB) metric for non-cooperative, unresolved target (point source object in beam projection applications)
- distributed time-varying speckle metric for non-cooperative, resolved target (extended object in beam projection applications)

Feedback controllers were implemented based on two algorithms: (1) stochastic parallel gradient descent (SPGD) and (2) multi-dithering.

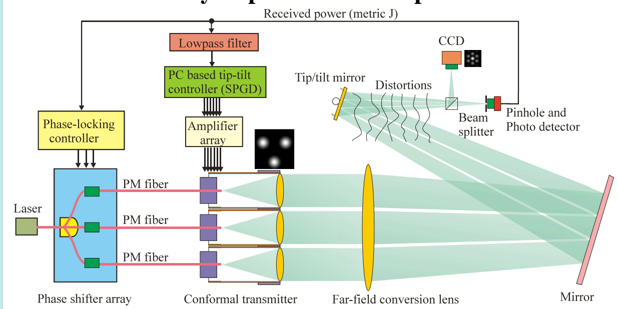
AVR microprocessor-based SPGD controller (8 channels, 16MHz clocking, 95,000 SPGD iterations per second, ±6π radian phase shift)

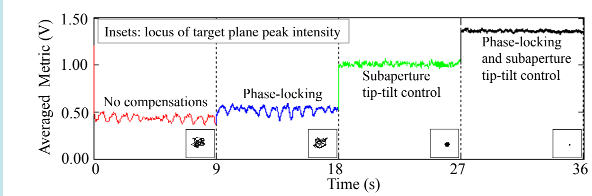


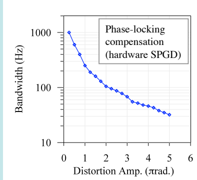
VLSI multi-dithering controller (8 channels, ±6π radian phase shift, dithers: ±0.01π radian, 1.0KHz~200MHz)

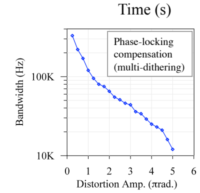


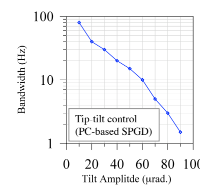
3. Laboratory Experiments: Setup and Results











Special thanks to:

Dr. Thomas Weyrauch, Dr. Ernst Polnau, Dr. Leonid Beresnev, Dr. Andrei Rostov and Dr. Dimitrios Loizos

Primary references:

- M. Vorontsov, "Adaptive photonics phase-locked elements (APPLE): system architecture and wavefront control concept," Proc. of SPIE V. 5895. 2005
- L. Beresnev and M. Vorontsov, "Design of adaptive fiber optics collimator for free-space communication laser transceiver," Proc. of SPIE V. 5895, 2005
- M. Vorontsov and V. Sivokon, "Stochastic parallel-gradient-descent technique for high- resolution wave-front phase-distortion correction," J. Opt. Soc. Am. A, V. 15, 1998
- T. R. O'Meara, "The multi-dither principle in adaptive optics," J. Opt. Soc. Am. 67, 306-315 (1977)
- L. Liu, M. Vorontsov, E. Polnau, T. Weyrauch, and L. Beresnev, "Adaptive phase-locked fiber array with wavefront tip-tilt compensation," Proc. of SPIE V. 6708, 2007