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

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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 $r_0$, a measure of atmospheric turbulence-induced phase distortion strength, and is independent of subaperture diameter $d$, if $d > r_0$. 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 $r_0$ if only phase-locking (piston) control is used. When on-subaperture adaptive optics (AO) compensation for low-order wavefront Zemike 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 smallest circle enclosing all subapertures and same beam profile can behave like monolithic aperture system with equivalent aperture.

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

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, 8-bit radian phase shift, dithers: ±0.01 radian, 5.0KHz~200MHz).

2.2. Multi-Channel LiNbO3 Polarization Maintaining Phase Shifter Array

F3. Laboratory Experiments: Setup and Results

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

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

$$\delta \phi = \frac{\pi}{r_0} (V - V_0)$$

Feedback signal for control systems: $\frac{\pi}{r_0} \left( \frac{V}{V_0} - 1 \right)$, where $V_0$: 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)