Experimental study of phase locking of fiber collimators using internal beam-tail interference.

Leonid A. Beresnev[1*], Mikhail A. Vorontsov[2], Thomas Weyrauch[2], Gary Carhart[1], Svetlana L. Lachinova[3,4], and Jiang Liu[1].

[1] US Army Research Laboratory, 2800 Powder Mill Road Adelphi MD 20783

[2] University of Dayton, School of Engineering, 300 College Park, Dayton, OH 45469 USA

[3] University of Maryland, College Park, MD 20742

[4] Optonicus, 300 College Park, Dayton, OH 45469 USA

[*]Corresponding author: lberesnev@arl.army.mil

ABSTRACT

Experimental study of internal phase locking of a seven fiber collimator array is presented. As a metric for the feedback loop the periphery areas (tails) of beams outgoing from three adjacent fiber tips are used *before* the beams are clipped by the lens apertures. The "intercepted" tails of beams are redirected back into the collimator array forming an *interference pattern* located between adjacent collimators. Optical energy from one region of the pattern is selected by a pinhole, detected with a photo-diode and used as a metric signal for an SPGD controller to lock the phase of the three adjacent beam tails. The non-common phase difference of the outgoing wavefronts from these three collimators can be manipulated by altering the position of the pinhole in focal plane of the interference pattern and is removed (set to "zero" or 2π increments) by a displacement selected to produce the expected far field interference pattern. To phase lock the beams from seven collimators arranged in a hexagonal array, three pinholes, each of which receives some light from the center collimator are used. A sum of the signals from the three photo-diodes placed behind these pinholes is used to lock the phase of the six periphery beams to the central uncontrolled reference without beam splitters or a remote target-in-the-loop metric.

INTRODUCTION

Multi-aperture (sparse) laser transmitters are considered to be a useful strategy for increasing laser beam power while maintaining high optical quality for applications that must deliver high

Fiber Lasers VIII: Technology, Systems, and Applications, edited by Jay W. Dawson, Eric C. Honea,
Proc. of SPIE Vol. 7914, 79142Z · © 2011 SPIE · CCC code: 0277-786X/11/$18 · doi: 10.1117/12.877300

optical energy density to a small area at a target. The “tiled fiber laser” approach permits the construction of a high-quality high-power laser beam by means of combining the output from fiber optic collimators each projecting a modest power (~1kW) of laser radiation while preserving high beam quality ($M^2 < 1.2$). Furthermore, the diffraction limited spot size for the multi-aperture scheme is determined by the sparse (conformal) aperture *D* rather than the diameter *d* of output sub-apertures. To obtain the highest intensity at the center of the diffraction limited spot, the optical phases of all beams should be locked with high accuracy (a tenth of wavelength or better). For active phase-locking of an adaptive fiber collimator array [1] the stochastic-parallel-gradient-descend (SPGD [3]) control strategy is considered a robust and reliable method for optimizing both the piston phase variations in fibers and tip/tilt wandering of beams as they propagate through atmosphere .

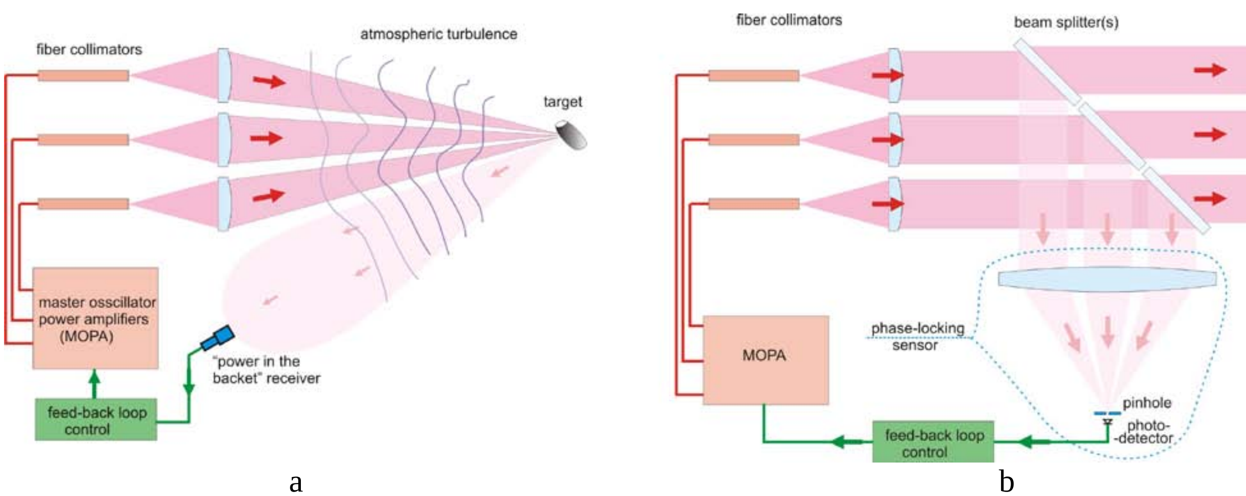


Fig.1. Two schemes of phase-locking the conformal laser beam transmitter with external feedback metric.

In Fig.1. two approaches are shown realizing SPGD control systems using as a feedback metric the optical power collected in a receiving aperture, i.e., a power in the bucket (PIB) metric, from (a) the laser radiation scattered at the target, or (b) intercepted with beam splitter(s) placed in the outgoing beam train. In both cases the wavefronts of beams leaving the sub-apertures have random phase until the external feed-back loop is closed. SPGD [1, 3], as well as multidithering [4, 5], control strategies require external elements outside of the transmitter (i.e., a remote target-in-the-loop or a beam splitter in close proximity to the fiber array) to obtain the signal required for phase-locking of the laser beams (beamlets) composing the sparse aperture.

In reference [2], an internal feed-back loop control strategy is proposed for locking the beam phases before they leave the collimator array pupil. This control strategy does not use a metric obtained from a target-in-the-loop or beam splitters located in the train of laser beams.

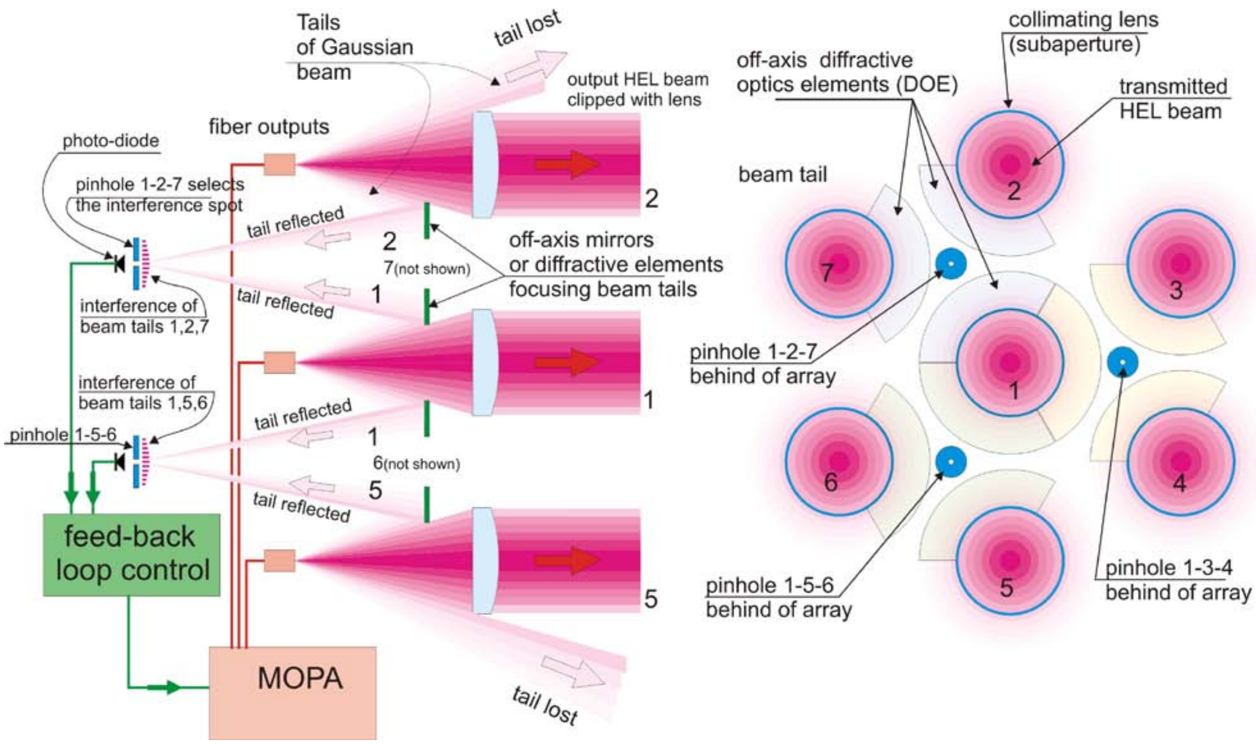


Fig.2. The use of clipped Gaussian beam-tails as a source of in-pupil metric for phase-locking of seven coherent beams [2].

The approach is based on the use of the periphery areas (tails) of Gaussian intensity distributions which in the collimator are clipped at the output lens apertures before the beams leave the collimators. According to this approach the optical power in the clipped area (up to 10% of the entire Gaussian beam power) can be used as a carrier of optical phase information of the collimator beams to define another metric that can be used to close the control loop (see Fig. 2). Reference [2] describes this internal feedback technique using a “two-tail sensor” or “three-tail sensor” when the photo-sensor defining the feedback metric is placed into an interference pattern formed with two or three overlapping beam tails. For practical realization it was supposed that 1) the tail beams clipped near the pupil plane (collimator lenses plane) are redirected back to the fiber array in between collimators providing longer distance for tail interference and hence larger size of interference spots compared to those formed in pupil plane (estimations give these sizes in range of microns). 2) Three-tail interference is more practical than two-tail one particularly in case of hexagon arrangement of array collimators [1], because of easier installation and alignment of pinhole-photodetector (PH-PD) assemblies.

EXPERIMENT

Optical scheme. Hardware realization.

The experimental setup, shown in Fig. 3, is based on the adaptive array of phase locked collimators, described in paper [1].

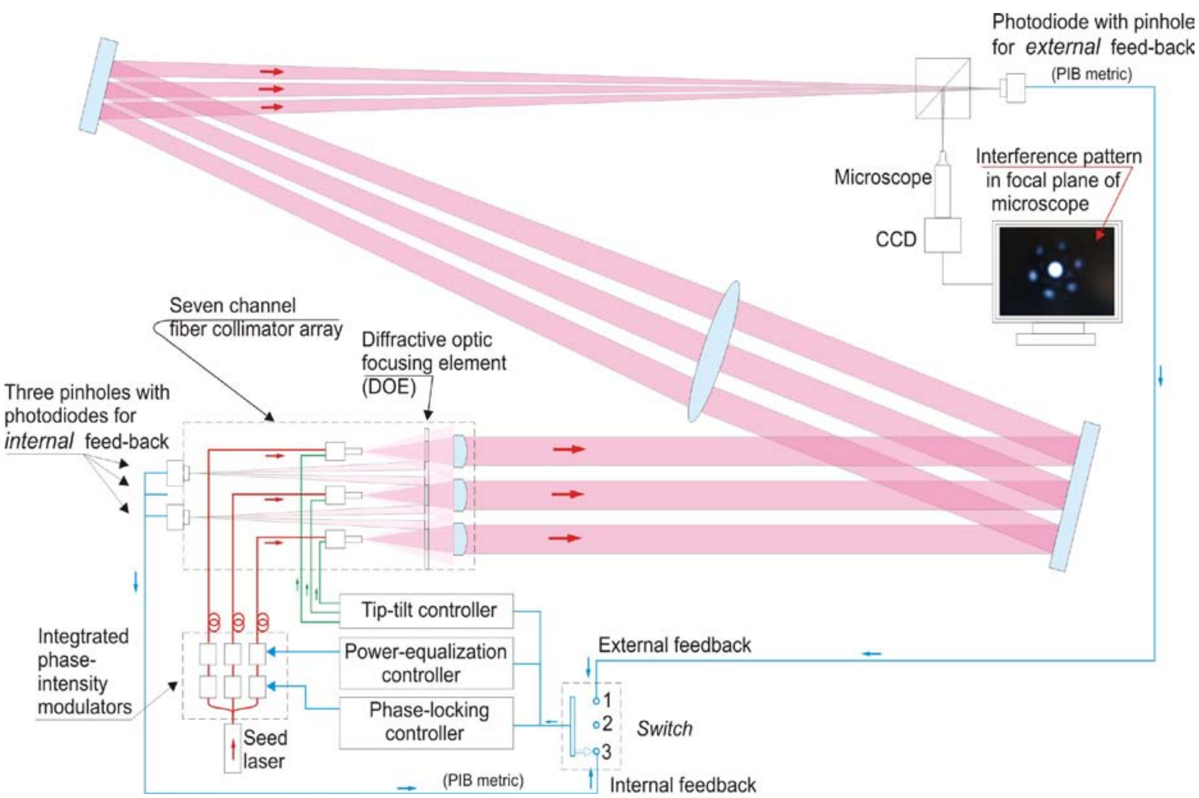


Fig.3. Experimental setup for phase-locking of seven fiber collimators using external or internal feedback control loops.

The significant modification of the system discussed in present paper, is the addition of two elements required to realize the internal feedback control loop (see Figs. 4 and 5).

PH-PD's area Fiber collimators area Array body DOE Output lenses

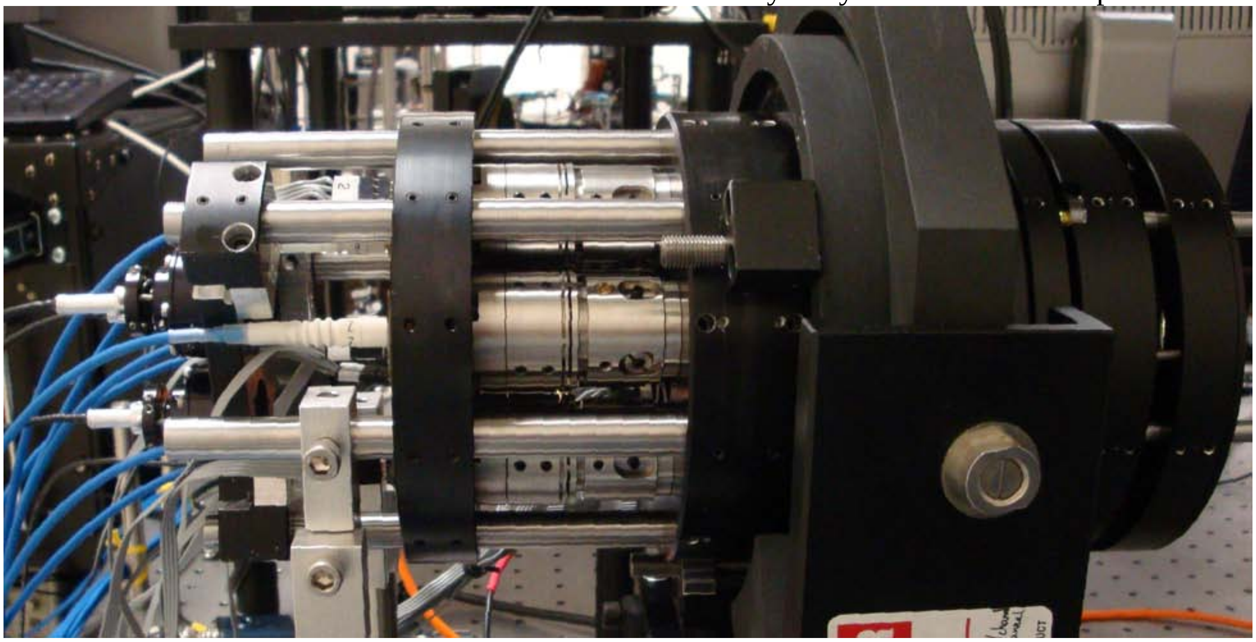


Fig.4. Side view on seven fiber collimator array with internal feedback control. Gaussian beams coming to the right from fiber collimators are clipped with output lenses. The beam tails are intercepted with diffractive optic element (DOE) and returned back in-between collimators to pinhole-photodiode (PH-PD) area.

These elements are shown in Fig. 2 as 1) diffractive optic elements (DOE) and 2) PH-PD assemblies placed on back side of collimator array.

1) Diffractive optic element.

This element is placed inside of the seven applet cluster close to the collimating lenses. The element contains a number of off-axis reflecting diffractive optic mirrors fabricated by a multi-layer holography technique on glass substrate (see Fig. 5).

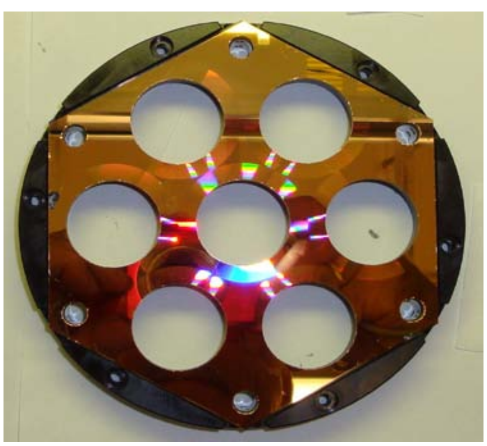


Fig.5. Diffractive optic elements (DOE) on glass substrate (in metal holder). Distance between hole centers 37mm.

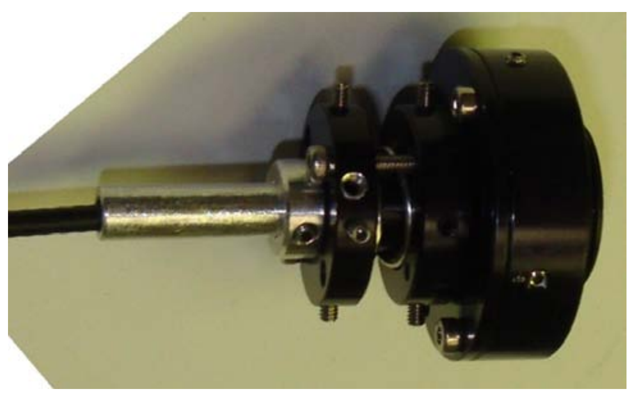


Fig.6. Pinhole-photodiode (PH-PD) assembly with six degrees of freedom for alignment of pinhole and photo diode.

Reflective banana-shaped areas are located around each collimating lens and intercept and reflect the beam-tails of the Gaussian beams before they are clipped with lens apertures.

After reflecting back the beam-tails are focused between three adjacent collimators in a focal plane on the back of the cluster body (see left side of array in Fig. 4). The optimum interference pattern formed from the three beam-tails is located far enough from the fiber positioners to provide space for pinholes and photodiodes.

2) Pinholes-photodiode (PH-PD) assembly.

Both the PH and PD were unified in one assembly with six degrees of freedom (see Fig. 6), providing the possibility for fine alignment of the photodiode relative to the pinhole and fine alignment of the pinhole within the optimum area of the interference pattern.

The "three-tail sensor" scheme ([2], Part 4) was realized in a hexagon arrangement of the seven beamlets. Three PH-PD assemblies were used to provide the feedback metric for the SPGD controller. The metric signal defined for SPGD control was the sum of signals from all three photodiodes.

The central channel, No.1 in Fig. 2, had no phase shifter and served as a phase reference beamlet for the three groups of beamlets: 1-2-7, 1-3-4, and 1-5-6.

Alignment of DOE, search of 3D location of optimum three-tails interference.

As it is shown in Fig. 2, the signal from each photodiode used for phase-locking of three adjacent beamlets was initiated with power of interference spot combining the interference of three beam-tails focused behind of collimator array. For instance sub-apertures 1, 2, 7 provide the combination of intercepted beam tails in the area of pinhole 1-2-7. The diameter of pinhole is of the order of 10-15 microns and the optical power of the light exiting the pinhole was found to be on the order of tens of nano-Watts. For reliable operation of the SPGD control loop with MHz bandwidth, the signal from PD must be high enough, hence the pinhole should be placed in the area with highest optical power.

Using a CCD camera supplied with microscope objective (see Fig. 7), the area of optimum interference was found. The spatial dimension of this area was 200-300 μm in X and Y directions and about 500-1000mkm along Z-optical axis (see Fig. 8).

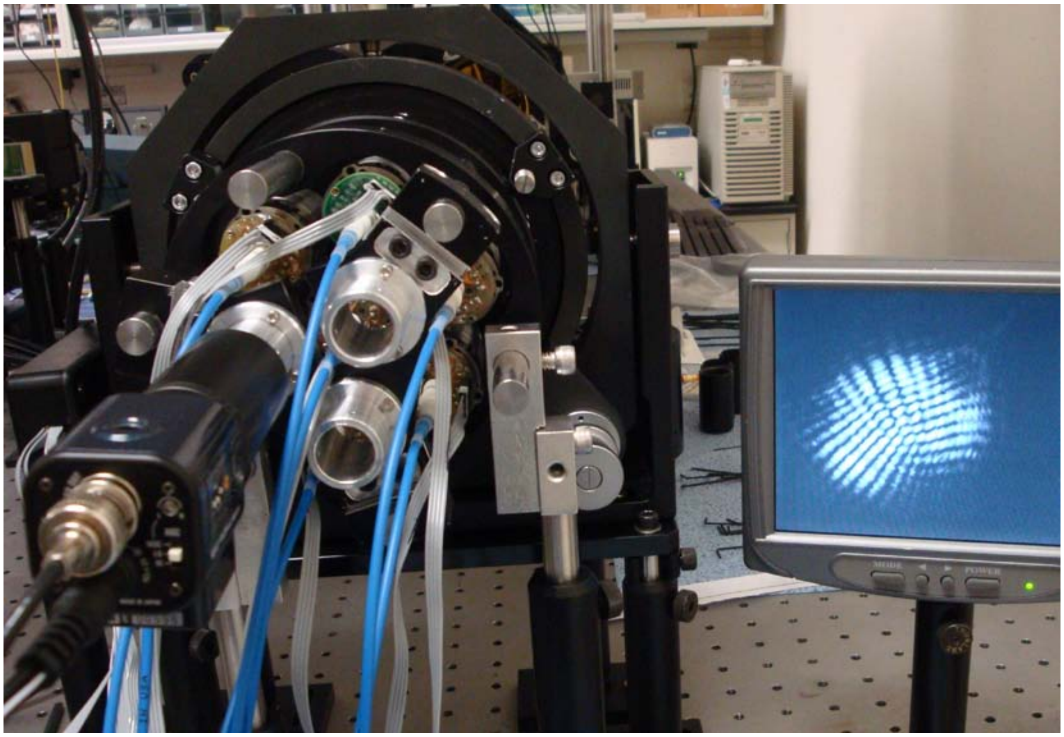
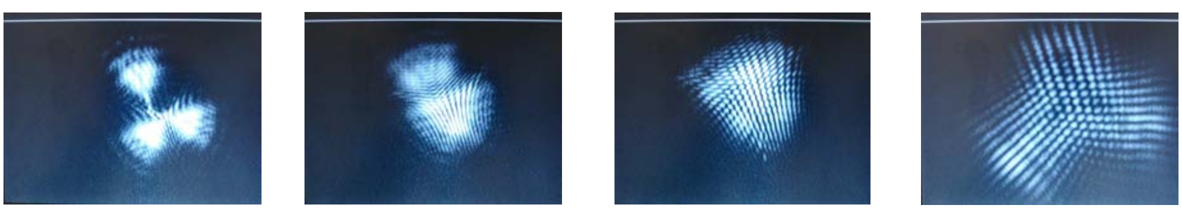


Fig.7. CCD camera with micro-objective allowed us to search the optimum interference pattern.

The localization of this area was accomplished by iteratively scanning the CCD-camera along Z for successive changed positions of DOE holder.



a b c d

Fig.8. Variation of interference pattern from three intercepted beam tails in dependence on position of CCD focal plane at fixed position of DOE. Size of screen is 600x400mkm. The focal plane with pattern (c) can be considered as an optimum position for pinhole which selects the interference spot for internal feedback control of phase-locking. Spot size is of the order of 15μm.

Installation and alignment of PH-PD assembly in optimum interference location.

After roughly finding the interference pattern location the CCD camera was replaced with PH-PD assembly. Further optimization of the PH-PD location was accomplished with fine X-Y scanning of this element to maximize the signal from photodiode.

This procedure was repeated for the other two PH-PD assemblies, 1-3-4 and 1-5-6. As a metric for the SPGD controller the summed signal from the three photo-diodes was used.

Activation of coherent phase-locking of the seven beam system with *external* feed-back control. Obtaining the reference interference pattern for performance evaluation of *internal* feedback control.

For evaluation of *internal* feed-back loop performance the seven beamlet cluster was aligned and activated using the *external* power-in-the-bucket feedback metric scheme (see [1], Part 3, Fig. 6). The alignment process and controlling apparatus for the *external* feedback scheme is described in [1]. Channel power equalization, tip-tilt controller and piston phase-locking controller were all activated to obtain the best phase-locked interference pattern with bright central diffraction limited spot accompanied by small-intensity side lobes ([1], Fig. 7b). The “far-field” CCD video-camera with microscope objective was used to capture the interference pattern in focal plane of long-focus lens.

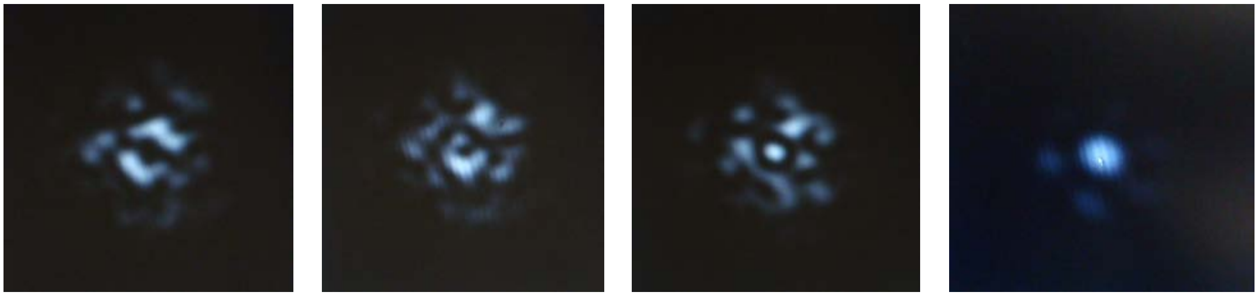
This pattern obtained with the *external* (PIB) feedback loop was used as a reference for evaluation of the pattern observed in the same focal plane but using the *internal* feedback system. The re-arrangement of system from external feedback loop to internal feedback loop was accomplished by switching the input of the phase-locking SPGD controller from external photodiode with pinhole located in the far-field to internal PH-PD assemblies located behind of collimator array, Fig. 3.

Setting of non-common phase difference to 2π increment between beamlets.

In Fig. 9a) the far-field interference pattern is shown when the internal feedback loop was turned on for phase locking of three adjacent beamlets 1, 2, and 7. The other channels (3, 4, 5, 6) were blocked and did not participate in the interference. The wave-fronts from three beamlets are locked with some occasional but constant non-common phase differences leading to the occasional interference pattern.

It was suggested [2] that non-common phase differences between beamlets can be set to 2π N , where N is the integer, using outer phase modulators with stroke about one wavelength. Another way suggested in [2] is the X-Y-scanning of pinhole 1-2-7 to obtain the 2π increment between these three beamlets, Fig. 10.

We scanned manually the pinhole 1-2-7 until the far-field interference pattern repeats the quality of reference pattern obtained with external feedback control, Fig. 9d). Obtaining the correct summed wave-front from three neighboring beamlets can be also accomplished automatically by using an additional SPGD feedback control system with *PIB metric from far-field* PH-PD and motorized X-Y positioning of the *internal* PH-PD assembly.



a b c d

Fig.9. Transformation of interference pattern from three beam tails 1-2-7 observed in far-field during the X-Y scan of PH-PD-1-2-7. Pattern d) is close to the reference pattern obtained with external feedback control (bright central spot and weak side lobes).

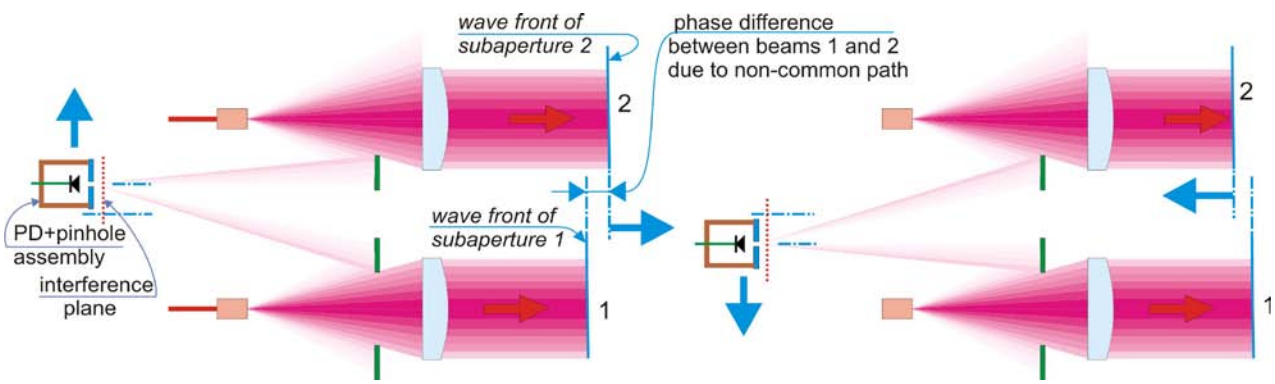


Fig.10 a) Mutual displacement of wave fronts from beamlets 1, 2 and 7 (wave fronts of beamlets 1 and 2 are shown) at scanning the position of pinhole in focal plane of interference pattern.

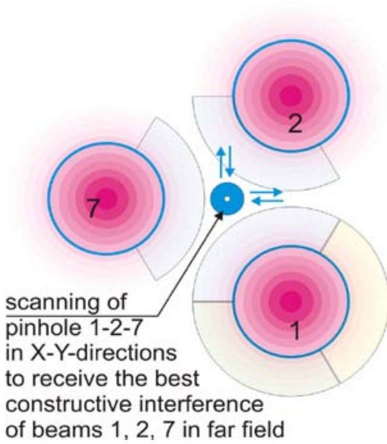


Fig.10 b). Scanning of pinhole 1-2-7 in focal plane of interference pattern formed with intercepted and reflected back beam tails of beamlets 1, 2 and 7.

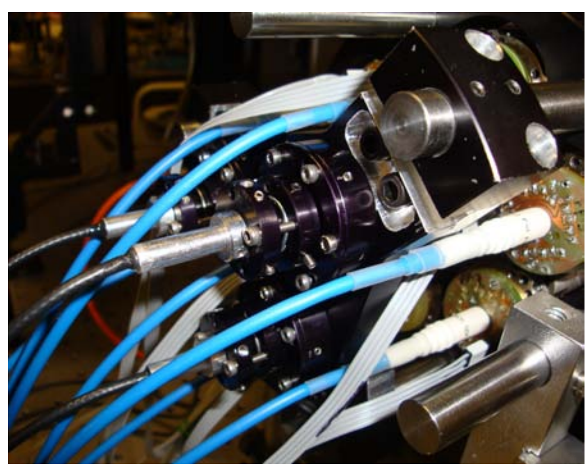


Fig.10 c). PH-PD assemblies located on back of seven beamlet array. Each from three assemblies has six degrees of freedom.

The same processing was accomplished with pinhole 1-3-4 after closed channels 2, 5, 6, 7, and with pinhole 1-5-6 after closed channels 2, 3, 4, 7. In the second and third cases similar quality interference of three beams was obtained as shown in Fig. 9d). Note that central collimator serves as a reference wave front collimator with no phase control. Wave fronts of all the other collimators were set to the same phase as collimator 1 (to within an integral number of wavelengths).

Then all output collimator apertures were open. The interference pattern observed with CCD camera in far-field is shown in Fig. 11b) and has close to the same quality as the pattern received with external feed-back loop (PIB) control, Fig. 11a).

a	b	c	d
External - ON	Internal-ON	Internal-OFF - 5sec	Internal - OFF-10sec

Fig.11. a) Reference interference pattern in far-field obtained with external feedback control; b) interference pattern observed in far-field if the internal feedback loop is ON; c) and d) – changes of interference pattern if feedback is turned OFF, characteristic change time is a fraction of second.

Stability.

In the set of photos in Fig.12 the long-term conservation of the interference pattern is shown if the internal feedback control is ON. There are no significant changes in far-field pattern during tens of hours with ambient temperature variation in range of about 5^{o}C.

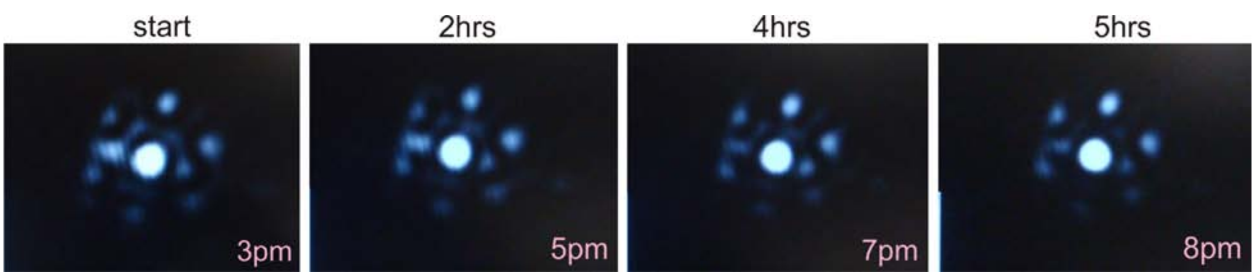


Fig.12. Stability of the constructive interference in far-field for seven beams phase-locked using internal feedback loop.

CONCLUSIONS

The phase locking of seven beamlets in a sparse (conformal) multi-aperture system was accomplished using internal feedback configuration.

As a input metric for feedback loop the combination of periphery areas of Gaussian beams (beam-tails) were used. Diffractive optics elements intercepted the beam tails and focused them to back of fiber collimator array forming an interference pattern. The brightest interference spot from the pattern was selected with the pinhole-photodiode assembly and the PD signal served as a metric for phase-locking the three adjacent beamlets.

The setting of non-common phase difference between three beamlets to 2π increment was accomplished by means of PH-PD-assembly scanning in plane of interference pattern formed with intercepted beam tails.

An internal metric feed-back loop using the interference of the periphery Gaussian beam tails allows us to obtain a diffraction limited beam without the use of external remote target or bulky beam splitter(s) in the output beam train. A high-quality high-power beam can be obtained in a kW beam combining array effectively using the parasitic beam tails inside of array, which would otherwise leading to overheating problems.

REFERENCES:

1. Mikhail A. Vorontsov, Thomas Weyrauch, Leonid A. Beresnev, Gary Carhart, Ling Liu, and Konley Ashenbach, “Adaptive Array o Phase-Locked Fiber Collimators: Analysis and Experimental Demonstration”, IEEE Journal of Selected Topics in Quantum Electronics, Vol.15, No.2, March/April 2009, pp.269-280.
2. Mikhail A. Vorontsov, Svetlana L. Lachinova, Leonid A. Beresnev, and Thomas Weyrauch, “Obscuration-free pupil-plane phase locking of a coherent array of fiber collimators”, J. Opt. Soc. Am. A, Vol.27, No.11, November 2010, pp.A106-A121.
3. M. A. Vorontsov, G. W. Carhart, and J. C. Ricklin, “Adaptive phase-distortion correction based on parallel gradient-descent optimization:, Opt. Lett. **22**, 907-909 (1997).
4. T. R. O'Meara, “The multidither principle in adaptive optics”, J. Opt. Soc. Am., Vol.67, 306-315 (1977).
5. T. M. Shay, “Theory of electronically phased coherent beam combination without a reference beam”, Opt. Express **14**, 12188-12195 (2006).