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Small footprint phase locking system for large tiled aperture laser array

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Abstract: A phase sensing system fitted to the control of coherent laser beam array of large cross section is experimented. It is based on the use of a fiber bundle that collects a weak part of the synthetic wavefront, that scales it down (1/40) and that reshapes it in a more compact arrangement (2D to 1D array). Then, the reconfigured beam array can be analyzed by a small footprint system making the large laser beam array easier to phase-lock. The discrete laser array wavefront transmitted by the meter long fiber bundle was stabilized thanks to a multiple arm servo loop. Laser array phase locking was further ensured by random scattering through a diffuser, associated to an alternating projection algorithm. Six fiber laser beams constituting a 110 mm diameter synthetic aperture, were phase-locked with $\lambda/16$ accuracy.

Introduction

Coherent laser beams resulting from the splitting and parallel amplification of a master laser can be arranged into a tightly packed beam array to serve as a high power radiation source [1,2]. This multiple arm Master Oscillator Power Amplifier (MOPA) architecture is a way to circumvent the limitation of laser amplification, in bulk or waveguide amplifier, without reducing too much the beam quality. Laser arrays produce a combined beam of high brightness provided the different beams forming the composite output aperture are properly phase-matched. Many techniques have been developed to phase-lock the fields of a coherent laser beam array and to maintain synchronization despite the unavoidable perturbations in the laser chains. The most popular methods can be found in [2]. Research on coherent beam combining focused on fiber lasers because of their high efficiency and their kilowatt range output power. The challenges addressed these last years mainly regard the increase in the number of laser outputs that can be controlled [3-5], the ultrashort pulse regime [6] and the phase-locking on a remote target with turbulence-induced phase aberrations [7-10].

Looking for high powers means here increasing the number of lasers in the array and hence increasing the total transverse dimension of the delivered beam. The phase control of a coherent laser beam array of large cross-section, rises practical difficulties. In particular, phase-locking methods that analyze the phase state of the laser array in the near field do not seem directly compatible with large beam array. Indeed the array cross-section must fit in the size of a camera sensor for analysis. This obliges to the use of large mirrors or lenses and long free space propagation to achieve beam reduction with a telescope, or display of the array far field, or generation of a reference plane wave of large cross-section, owing to the chosen phase-locking technique. Therefore, the phase-locking system should be bulky and heavy. To avoid these drawbacks, one option consists in using a feedback signal from the reflection of a far distant target, where all the laser fields interfere. Based on that signal, the phase of the different laser elements can be adjusted properly by an iterative wavefront control algorithm (target in the loop Stochastic Parallel Gradient Descent SPGD). However, the main objective of such a configuration is to compensate for the relative phase error accumulated by the laser beam array from the amplifiers up to the target, including the atmospheric turbulence. The coherent laser array with the largest dimension reported today (23 cm) has utilized this architecture [10], but the technique requires a sufficiently strong power reflection from the target and a great number of beams impairs its speed.

In the work presented below, we investigated an innovative scheme for achieving a large phase-locked laser array using a compact device. It involved an optical fiber bundle for collecting a sample of the laser fields and for their delivery to a phase analysis device, in a scaled down and reshaped version of the large array output. Many phase sensors and phase-locking system could be utilized with this compacted beam array. The global phase analysis device we have chosen was associated to an optimization process to reach phase locking and it realized the first implementation on a fiber laser array of a recently proposed innovative

technique [5]. See Fig.1 for a schematic picture of the proposed scheme with its two main devices, one for coherent downsizing by an optical fiber array and one for phase sensing.

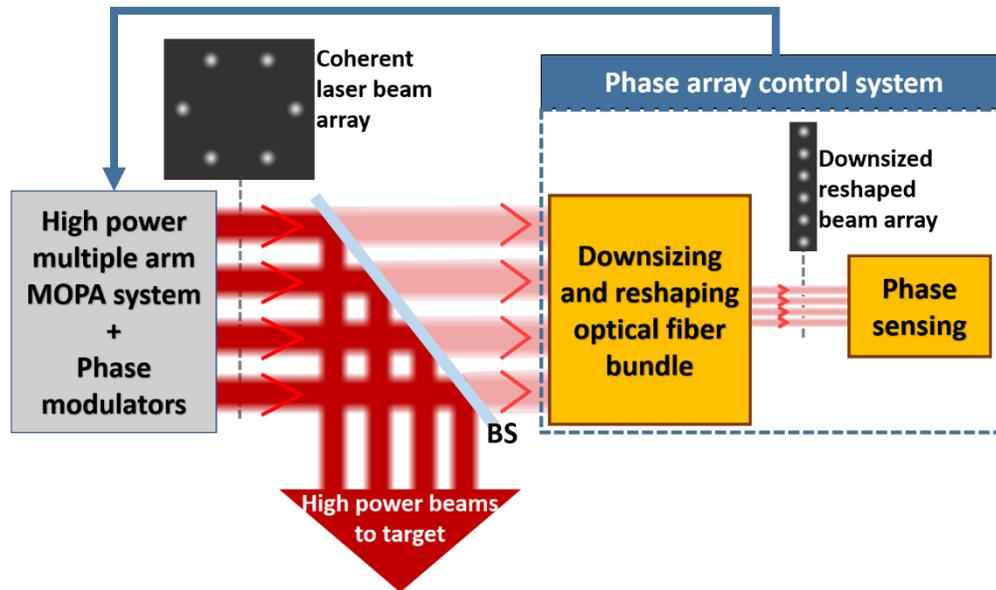


Figure 1: Schematic drawing of the architecture implemented in the experiment for phase control of a laser beam array of large cross-section. Insets show images of the 2D input beam array and of the scaled-down and reshaped 1D-beam array.

Principle of the method

Let us first introduce the downsizing device. Beam array remapping and densification have been already considered in the frame of interferometric optical imaging systems for astronomy based on diluted composite pupils. It led to the hypertelescope concept, an instrument that could provide direct images of stellar objects at high resolution [11]. A fibered version of hypertelescope has been proposed and further investigated [12]. In the laser beam array context, a similar optical fiber device would be relevant for downsizing the fraction of the laser output that feeds the phase control system. It is common practice to split the array output into a low power fraction for phase control and a high power fraction, which is directed toward a remote target. Scaling down the size of the discrete wavefront in the low power arm is a way for using compact wavefront sensing (WS) devices for the control of beam or array of large size. A fan in fibered device would certainly be the most compact and lightweight system for that purpose [13]. However, in the most general case, the optical path length differs from one fiber to another so that an optical fiber bundle does not realize a stigmatic optical system. Furthermore, optical path lengths in the bundle also vary in time because of environmental perturbations (temperature, vibration, acoustic waves). In order to preserve the discrete initial wavefront after its transmission by the bundle, each individual fiber must behave as a lambda wave plate. At least, if the wavefront is transmitted with some phase distortion, it must be known and stable according to time in order to be taken into account in the phase control process. In any case, to maintain the transmission condition fixed, whatever the environmental perturbations, a servo control is required. An additional benefit offered by the flexibility of optical fiber bundle is reshaping. A 2D array can be transformed into a 1D array for example or the lattice of the array can be changed.

The second part of the investigated scheme deals with the phase control of the individual emitters in the laser array, which relies on scattering and optimization algorithm. The different beams propagate through a scattering plate (a diffuser), in order that they all interfere with each other, creating a speckled multiple interference pattern. Then a diluted array of small photodetectors performs a sparse detection of the speckle intensity. The measured data feed a phase retrieval algorithm giving an initial guess of the laser fields. From the estimation, one derives the set of phase corrections to apply to the different beams, by means of their individual electro-optic modulators, in order to get the desired phase pattern. A single round of correction is

not sufficient usually but the process is iterated and it converges very quickly. Details of the method have been reported in [5] but the technique was not previously demonstrated on a real MOPA fiber laser array.

Experimental setup

The experimental setup is depicted in Fig.2. The laser source was based on a CW laser diode master oscillator at 1064nm, which is pre-amplified, then split into 6 outputs, and further amplified in double stage polarization maintaining (PM) fiber amplifiers, each delivering up to 5W. Each amplification chain included an electro-optic modulator on the input side for individual tuning of the amplified beam phase.

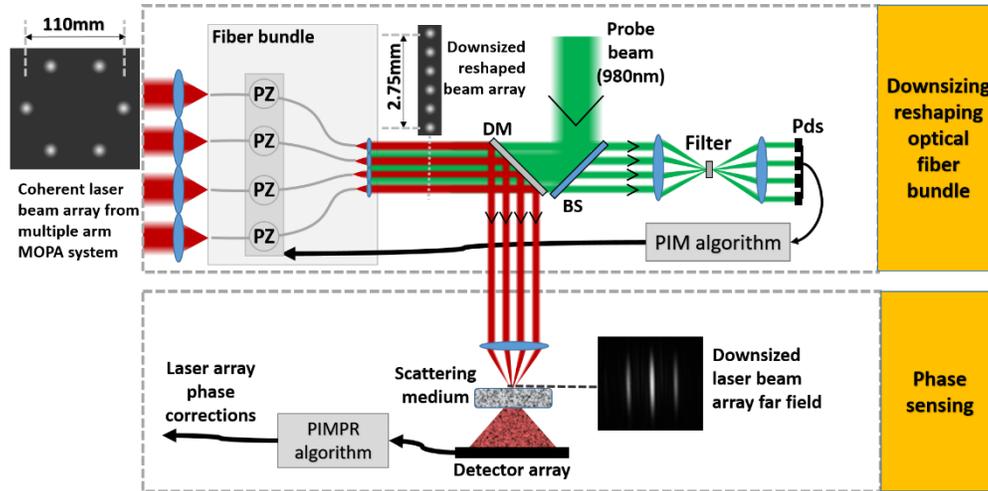


Figure 2: Schematic drawing of the experimental setup. The phase array control system is made of two main parts: downsizing and reshaping system and phase sensing device. PZ piezo-electric ceramic, DM dichroic mirror, Pds photodetectors, BS beam splitter, Filter phase-contrast filter. Experimental patterns of the six lasers beams @1064nm are shown in gray level, in the three locations where they are measured on the setup.

The six output beams (see Fig.1 and Fig.2) of Gaussian shape, 15mm in diameter at $1/e^2$, were periodically distributed along a ring of 110 mm diameter, leading to a filling factor of $\eta = 13.6\%$, considering the ratio between the laser beam diameter and the beam array diameter. This low filling factor was the consequence of large collimator positioners in this experimental setup, but it does not influence the phase locking process. A beam splitter sent a part of the beam array through a lens of long focal length (1.5 meters) to observe its far field. The figure above does not show this branch.

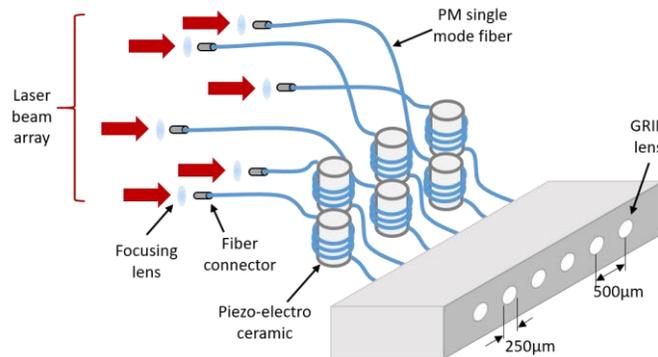


Figure 3: Schematic drawing of the fiber bundle made of 6 PM fibers, coiled on as many stretchers (piezo-electro ceramic). One end of the fibers collects the central part of the laser beams with small focusing lenses (5mm clear aperture, 18,4mm focal length). On the other end, the fibers are stuck to grin lenses periodically aligned

The other part was coupled into a bundle of PM optical fibers, which performed the downsizing and reshaping functions of the synthetic output beam (see Fig. 3). Each fiber of the bundle was wound onto a piezoelectric cylinder (PZ), for separate stretching and adjustment of the length of the various light paths. On the output side, the fiber bundle formed a linear array of fiber ends, stuck to GRIN lenses, on top of a silicon substrate with V-grooves. The 1D-array of 6 beams delivered by the fiber bundle covered a total section of $250\ \mu\text{m} \times 2750\ \mu\text{m}$ (6 Gaussian beams of $250\ \mu\text{m}$ diameter at $1/e^2$, equally spaced by $500\ \mu\text{m}$ on a line). It represented a 40-fold downscaling of the laser array output, despite the annular to 1D reshaping. In order to lock the fiber path length in the bundle and to make it robust with respect to perturbations, we used the Phase Intensity Mapping (PIM) phase-locking technique [14,15] together with a dedicated laser diode at $980\ \text{nm}$. A telescope with cylindrical lenses elongated the probe laser beam along one transverse dimension, before it passed through a dichroic mirror (DM) which reflected the signal at $1064\ \text{nm}$, and the beam coupled into the 1D fiber bundle. The light at $980\ \text{nm}$ made a roundtrip into each fiber thanks to reflective layers coated onto the fiber end faces, on the laser array side. After propagation through the bundle, the probe waves were subsequently analyzed by a phase-contrast imaging set-up. To ensure phase-locking of the probe beams (PIM technique), the measured intensity served as inputs for the servo which commanded the piezo voltages. Fig.4 shows the optical signal at $980\ \text{nm}$ detected by a photodiode placed in the far field of the bundle output and converted in phase standard deviation. The servo, when it was switched on, drastically attenuated the phase fluctuations below $0.2\ \text{rad}$ (rms). That means the PIM technique ensures stabilization of the fiber bundle with a standard deviation less than $\lambda/30$.

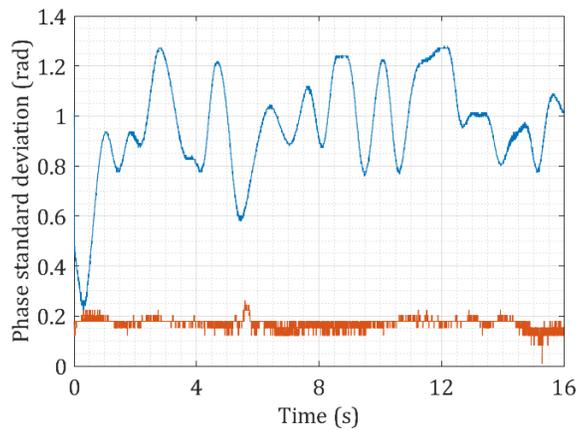


Figure 4: Probe signal at $980\ \text{nm}$ detected by a photodetector in the bundle output far field when the servo is off (blue) and when the servo is on (orange). The measured amplitude modulation is converted in phase standard deviation.

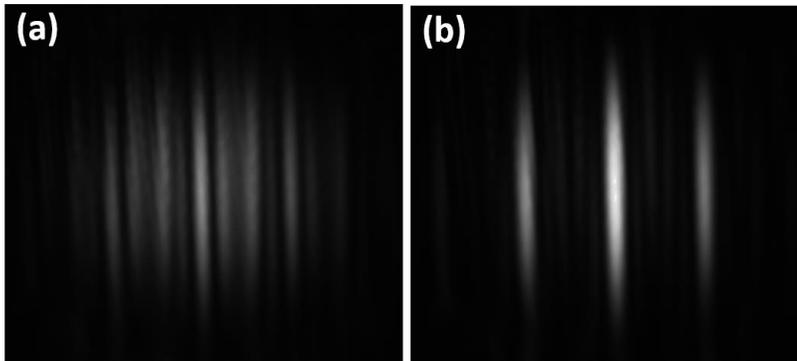


Figure 5: Experimental far field intensity of the 1064nm 1D beam array laser at the output of the stabilized fiber bundle. Typical pattern observed when (a) the second phase control servo (PIM-PR) is off and (b) when it is switched on. The phase corrections maximized the main lobe on the center of the far field pattern.

The technique of the first phase control system (PIM) is efficient only to lock to a similar value the individual phase piston within a beam array. However, it is mandatory that the second system, which controls the fiber laser array be capable of adjusting and preserving the phases on any desired profile. This is requested for compensation of the "aberrations" of the downscaling fiber bundle (once locked and stabilized). That is the reason why we implemented here the new PIM-PR technique [5] for control of the fiber laser array. It analyzed the optical field array at 1064 nm, after transmission and rescaling by the fiber bundle. In practice, the beams were focused on a diffuser and a line-scan camera measured the transmitted speckle intensity after 30 mm of free space diffraction. The phase corrections to apply on the different modulators of the amplifier array were computed from a sparse sampling of the camera data, according to the approach reported in [5]. At this stage, when the phase target was uniform, the PIM-PR phase control system locked the 1064nm beams delivered by the bundle to the in-phase state. The associated far field profile is well known and it can be easily recognized in the recording shown on Fig.5b. In the same time, on the 2D laser array side, the far field locked to a complex pattern (Fig. 6a), which is typical of beams with different phases. The phase change (piston offsets) between the reduced 1D beam array and the 2D laser beam array at 1064nm was due to the downscaling fiber bundle. The phase profile with reduced size delivered to the wavefront sensor differed from the actual phase distribution on the wide side. This came from the facts that the probe wavelength and the fiber laser wavelength were different and the probe waves made a double pass through the bundle. Maximization of the power detected by a photodiode placed in the center of the far field of the beam array, led to the compensation of these distortions. This was achieved by tuning the desired phase map in the PIM-PR algorithm. Tuning was done only on one beam at a time. At the end of the procedure, the set of phase offsets (desired phases) added in the laser phase control system gave the phase conjugated profile of the fiber bundle aberrations. The downsizing phase aberration remained stable as long as the bundle servo loop operated. Therefore, it became possible to get any phase profile on the wide 2D beam array from measurements done on the downscaled 1D beam array, just by including the aberration correction in the requested phase profile. As a typical example for demonstration, the wide laser beam array was set to the in-phase state as reported in Fig. 6b.

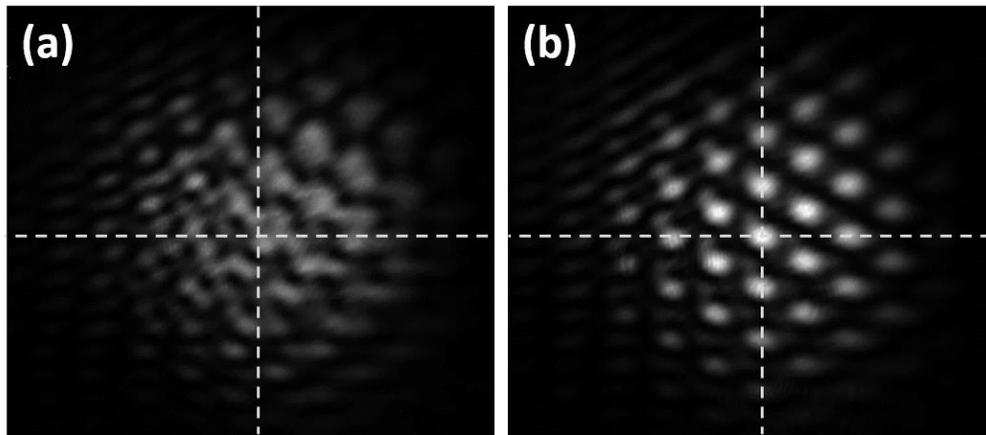


Figure 6: Experimental far field patterns of the ring beam array at 1064nm on the 2D wide laser output. a) Example of stable unstructured pattern when the 1D beam array, at the output of the down-scaling fibered system, is locked on the in-phase state at both the laser and probe wavelengths. Clearly, the phase was not uniform in the array. b) The in-phase pattern obtained when offset phases were adjusted in the PIM-PR algorithm to compensate for the distortions induced at 1064nm by the downscaling fiber bundle. Dotted crosshair shows the optical axis.

Phase sensing and control of the wide laser beam array was achieved using the iterative PIM-PR algorithm detailed in [5]. As predicted by previous numerical works, we experimentally confirmed, in an actual amplifying chain array, that this process requires very few iterations to converge to the desired phase profile. The parameter Q , used as combining efficiency on Fig. 7.a), denotes the ratio of the on axis coherently combined power P_{comb} to the maximum power that can be reached by summation of the six on axis individual amplitude $P_i^{1/2}$, defined as:

$$Q = \frac{P_{comb}}{(\sum_{l=1}^6 \sqrt{P_l})^2}$$

Fig 7 shows the dynamic behavior of the 1064 nm signal out of the fiber bundle measured by a photodiode located at the center of the signal far field. Multiple stop and go cycles of the PIM-PR algorithm, starting on different random initial phases, showed that the servo loop needed about 5 phase corrections to reach phase-locking on the in-phase state. The average combining efficiency was $Q=86\%$ (phase deviation less than $\lambda/16$ rms), with 2% standard deviation on 25 trials. It is also worth mentioning that these values cumulate the impact of the two phase control systems. As the servo loop bandwidth was close to 10 kHz, phase correction on 1064 nm signal was done in about 500 μ s, as confirmed by the Power Spectral Density (PSD) displayed on Fig. 7.b. PSDs were calculated from a typical single data time series when the servo was OFF (blue curve) and when it was ON (orange curve) The whole servo system maintained this stability and performance regardless of the operating time.

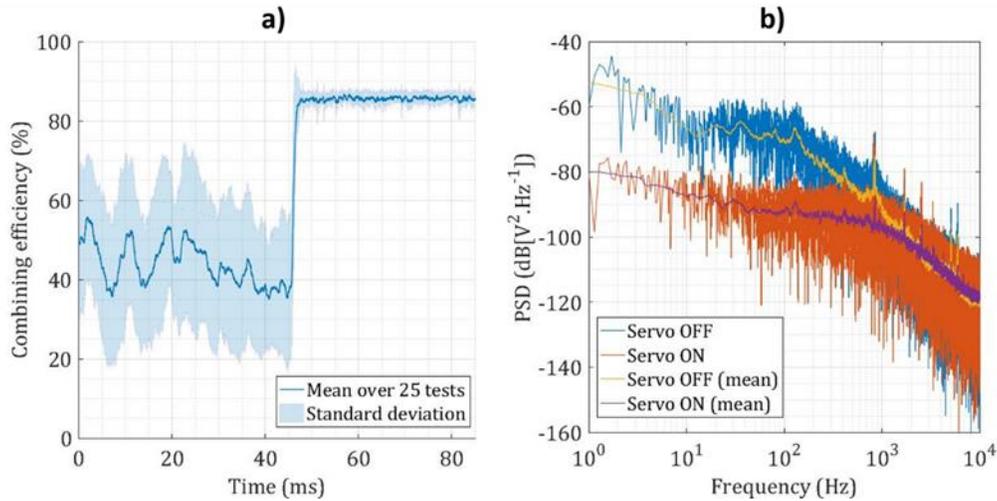


Figure 7: Dynamic behavior of the second phase control system (PIM-PR) operated through the stabilized fiber bundle. (a) Combining efficiency measured over 25 OFF-ON tests, starting on different random initial phases and (b) corresponding power spectral density (yellow and purple curves are the moving means of respectively the blue and orange curves, over 50 frequency samples).

Conclusion

We presented an innovative configuration to phase-lock an array of laser beams synthesizing a large output cross-section. A bundle of fibers collected phase information from the wide laser output to scale-down and to reshape the field array in a compact setting up, before transmission to the phase sensing system. A first dedicated servo, operated at a probe wavelength different from that of the laser, compensated for the slow optical path variations of the fiber bundle. The non-uniformity in the optical path, within one laser wavelength scale, of the different fibers of the bundle, was empirically determined and compensated by offsets, in the second phase control system devoted to the laser array. So individual optical phase monitoring and control in the wide beam array could be realized, after 40-fold reduction, in a highly compacted device, without being much impacted by the flexible reduction setup. The phase control system of the laser array, operated through the fiber bundle, was based on the recent iterative technique Phase Intensity Mapping using Phase Retrieval (PIM-PR). It was applied here for the first time, to an actual network of fiber amplifying chains, and it perfectly worked for locking the beam array on desired phase maps. This optimization technique only required an average of five iterations to converge to the targeted phase set, leading, in this specific setup, to almost 2 kHz phase-locking bandwidth. According to previous modelling [5], the bandwidth should be preserved for arrays of larger size with up to 100 beams. Because of the high flexibility of the fiber bundle feature, considering in particular the bundle length of 2.5 meters, this phase correction system, demonstrated here with a 110 mm wide laser array output, can be easily up-scaled to larger cross-sections. In addition, it allows remote phase control of the beam array, away from the amplified output.

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Disclosures

The authors declare no conflict of interest.

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