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# Coherent beam combining of 60 femtosecond fiber amplifiers

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## ABSTRACT

We report on the first coherent beam combining of 60 fiber chirped-pulse amplifiers in a tiled-aperture configuration along with an interferometric phase measurement technique. Relying on coherent beams recombination in the far field, this technique appears well suited for the combination of a large number of fiber amplifiers. The 60 output beams are stacked in a hexagonal arrangement and collimated through a high fill factor hexagonal microlens array. The measured residual errors within the fiber array yields standard deviations of 4.2  $\mu\text{m}$  for the fiber pitch and 3.1 mrad for the beam-to-beam pointing, allowing a combining efficiency of 50 %. The phasing of 60 fiber amplifiers demonstrates both pulse synchronization and phase stabilization with a residual phase error as low as  $\lambda/100$  RMS.

**Keywords:** Coherent Beam Combining, Femtosecond Lasers, Fiber Lasers

## 1. INTRODUCTION

A wide field of applications ranging from materials processing [1-3] to high-field physics [4] requires amplification laser systems delivering both high average and peak powers at high repetition rate and efficiency. It is now becoming a reality thanks to tremendous recent progresses in high power ultrafast thin disk lasers [5] but also in a more scalable laser architectural approach called Coherent Beam Combining (CBC) [6] with the kW average power horizon already exceeded for both technologies. The principle of CBC is to divide a single source into N independent channels, each with a dedicated amplifier. The outputs of the N amplified channels are ultimately coherently combined into one single beam, which carries N times the power of a single channel. For this recombination to be efficient, the phases of the sub-beams need to be adjusted such that they match one another [7]. The amplifiers of choice for the vast majority of CBC laser prototype currently studied or operated are fiber amplifiers. Such amplifiers carries indeed advantageous characteristics such as excellent beam quality, high efficiency and good thermal handling.

CBC can be performed either in filled-aperture or in tiled-aperture [8-10] configuration. The former exhibits higher combining efficiencies but often involves multiple combining elements so that the system complexity and thermal effect management increases with the number of fibers. On the other hand, aperture tiling leads to lower combining efficiencies but allows an easy stacking into a 2D array with very stringent pitch and angular positioning accuracies, a great number of fibers and performing beam combination in one single step without any combining elements.

However, applications in the field of high-energy physics, such as particle acceleration [11,12] and space debris removal [13,14], would benefit from the high average powers provided by fiber laser systems, but would require pulse energies of about 10 J. Considering the milli-joule level of a single emitter, several thousands of fibers need to be combined (> 10000 fibers). Thus, highly scalable CBC architectures along with an adequate phase measurement technique is needed.

The XCAN (Coherent Amplification Network) project a collaboration between the Ecole Polytechnique and Thales aims at experimentally exploring such laser architecture using a scalable Coherent Beam Combination (CBC) approach in the femtosecond regime. Our CBC prototype consists in coherently adding, in a tiled-aperture configuration, the output beams of 61 independent fiber amplifiers seeded by a common source, stacked in a hexagonal arrangement and collimated by a high fill factor hexagonal microlens array. The phase stabilization is performed using an interferometric measurement

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method with active phase control and beam combination in far field. This technique is well suited for the phasing of a large number of beams, since the recombination and the phase measurements are achieved in one single step. First proof of principles of the XCAN project have first been demonstrated with 19 passive fibers [10], and subsequently by 7 and 37 high power fiber amplifiers [15,16].

In this paper, we report on the CBC of 60 femtosecond fiber chirped-pulse amplifiers operating at moderate average power in a linear regime. This is to our knowledge, the first demonstration of a highly scalable CBC of femtosecond fiber amplifiers involving the tiled-aperture geometry along with the interferometric phase measurement and control.

## 2. EXPERIMENTAL SETUP AND RESULTS

The experimental setup is shown in Fig. 1. The master oscillator delivers 220 fs laser pulses at a repetition rate of 55 MHz. The pulses are temporally stretched up to 2.5 ns by a chirped fiber Bragg grating, followed by a pulse shaper common to all channels and used to pre-compensate the dispersion accumulated all over the chain.

The beam is then split into eight sub-beams, each one being again split into new eight sub-beams, all of them passing through individual phase and delay adjustment modules allowing independent adjustment of each of the 61 optical path lengths. This ensures an exact temporal overlap of all the pulses and a matching of their carrier envelop phases, thus leading to a stable and efficient coherent combination. Three pulse-picking stages based on acousto-optic modulators (AOM) are inserted into the laser chain to reduce the pulse repetition rate, allowing increasing the output pulse energy to study CBC in nonlinear regime. In order to compensate for power losses all over the laser chain, several pre-amplifier stages reset the average power at a 100 mW level. The 61 beams are power amplified using Large Mode Area ytterbium-doped Photonic Crystal Fibers of 30  $\mu\text{m}$  mode field diameter, supplied by NKT Photonics and functionalized by Optical Engines Inc. Co-propagative pumping scheme is considered. Pump and signal are injected into the fiber amplifier along the same direction, through a pump/signal combiner located before the active fiber. The amplified signal is then extracted through the output fiber without any obstruction from any other fiber components.

In order to arrange the fibers accurately in a hexagonal array and satisfying CBC tight geometrical arrangement, a dedicated high precision mechanical fiber holder was designed with a pitch of 3.2 mm. A measurement of the residual errors yields standard deviations of 4.2  $\mu\text{m}$  for the fiber pitch and 3.1 mrad for the beam-to-beam pointing. Except for the free space delay lines, our laser system operates with an all-polarization maintaining fiber front-end, thus guaranteeing a maximum of robustness and convenience of use.

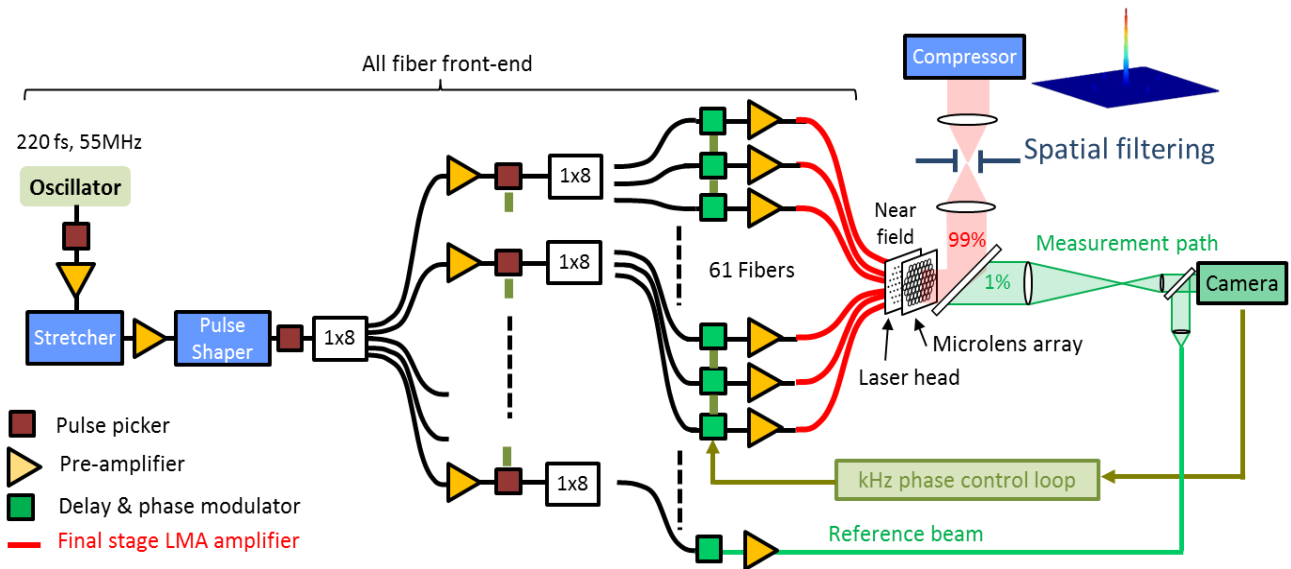


Figure. 1. Experimental setup for the CBC of 61 fiber amplifiers.

Several coherent addition approaches exist like Hänsch-Couillaud interferometry [17], Locking of Optical Coherence by Single detector Frequency Tagging (LOCSET) [18], Stochastic Parallel Gradient Descent (SPGD) algorithm [19]. Considering our architecture, the CBC is performed using the interferometric phase measurement method described in [10]. The remaining reference beam is used as a plane wave reference for the real-time phase measurement. A small power fraction of the composite near field is imaged onto a 1 kfps fast camera, where it interferes with an expanded reference beam for real-time phase measurement. This allows the acquisition of 60 interferograms on a single camera image, and the subsequent deduction of the relative phases between each channel and the reference beam.

A 1 kHz feedback algorithm acting on the phase modulators stabilizes these phases. Fig. 2 and Fig. 3 show respectively the experimental near field obtained with 60 amplified and collimated beams and the corresponding simulated (left) and measured far field (right) when the fiber array is phase-locked.

The periodic intensity distribution of the composite beam in the near field gives rise to secondary lobes surrounding the central lobe as observed on the far field. However, the beam quality is excellent and the good agreement between the measured and simulated far field confirms that spectral phase discrepancies between the 60 beams have a minor effect on the combination efficiency.

When operating the system at low power per channel ( $\sim 4$  W per fiber), 210 W of total average power is measured. The far field is then spatially filtered by truncating it at the first extinction of the ideal main lobe, where we measure a 105 W output average power for the combined beam, corresponding to a combining efficiency of 50 %. Taking into account microlenses array losses of about 8%, the final effective combination efficiency is 46 %. The remaining difference between this value and the theoretical one ( $\sim 67\%$ ) is due to some misalignments in the fiber array, polarization orientation errors and the missing channel.

Finally, the combined and spatially filtered beam is temporally compressed using a 1760 l/mm multilayer dielectric reflection grating pair from Plymouth Grating Laboratory. Based on the measured spectrum shown in Fig. 4 (right), we calculate a Fourier Transform-limited pulse duration of 212 fs and an autocorrelation function as shown in Fig. 4 (left) with a FWHM of 223 fs. At the compressor output, the measured average power of the combined beam is 92 W, leading to a compressor efficiency of 82 %.

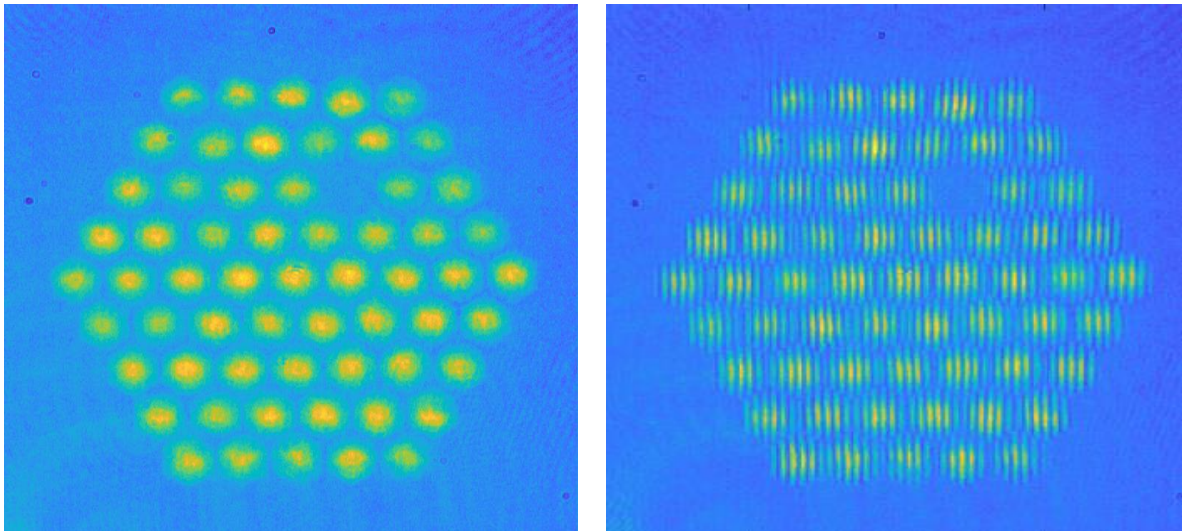


Figure 2. Near field of 60 beams without (left) and near field interference pattern (right) recorded with a reference plane wave for phase measurement (the missing channel was removed for maintenance purposes).

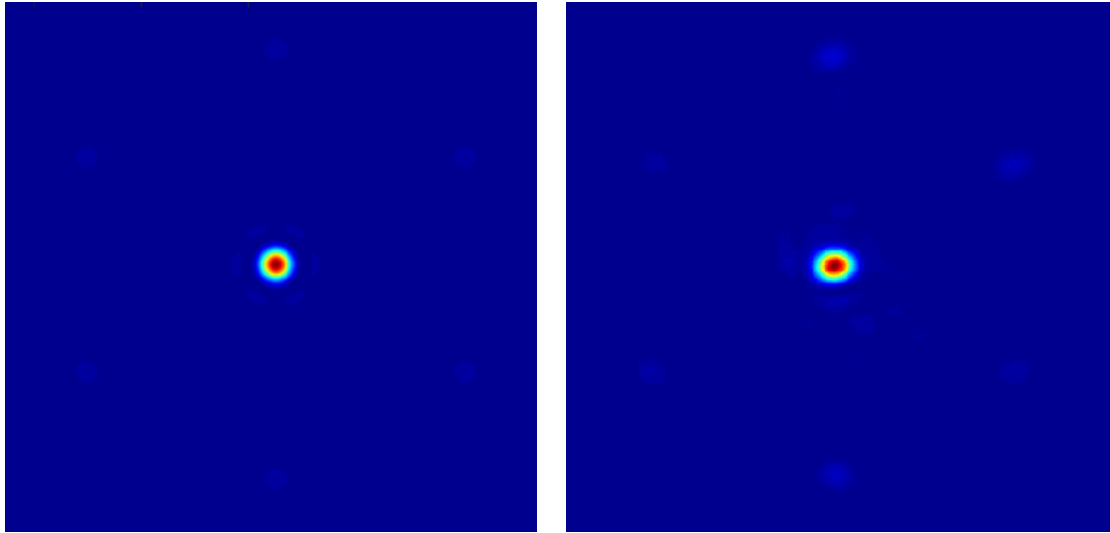


Figure 3. Simulated (left) and experimental far field (right) obtained with the CBC of 60 beams.

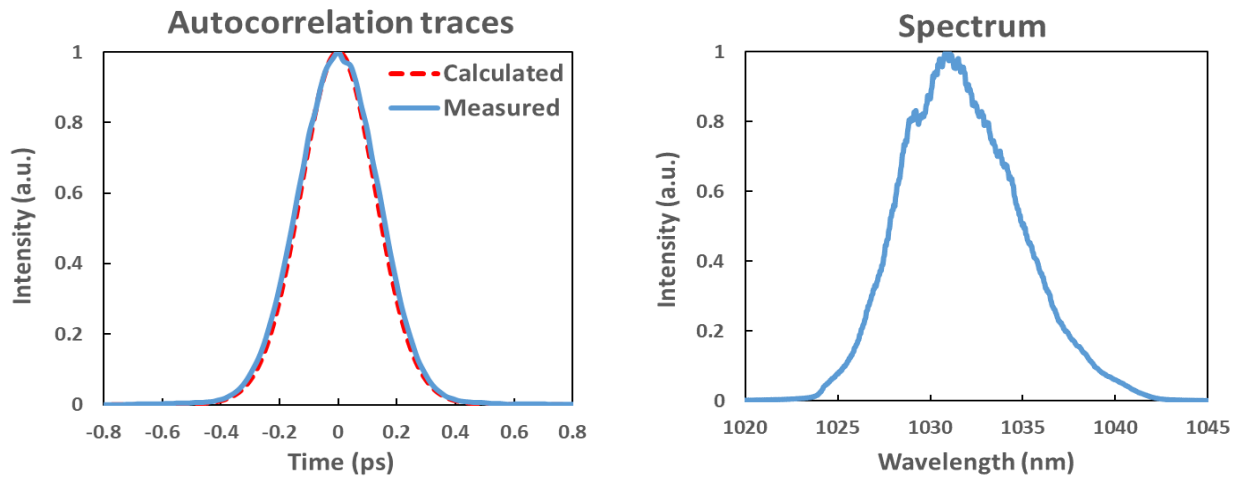


Figure 4. Autocorrelation functions (left) and spectra (right) of the combined beam in linear regime.

The phase locking is evaluated by measuring the phase noise between two fiber amplifiers operating in linear regime. The relative phase is retrieved by generating interference fringes between the two beams and simultaneously recording the interference states in quadrature using two independent photodiodes. Figure 5 gives the phase noise density of the measured relative phases in open and closed loops, respectively.

The feedback algorithm clearly reduces the low-frequency noise by more than five orders of magnitude in the low frequency band, yielding a residual phase error of  $\lambda/100$  RMS between two fibers. The peak around 100 Hz is due to general laboratory noise including the laboratory air conditioning system.

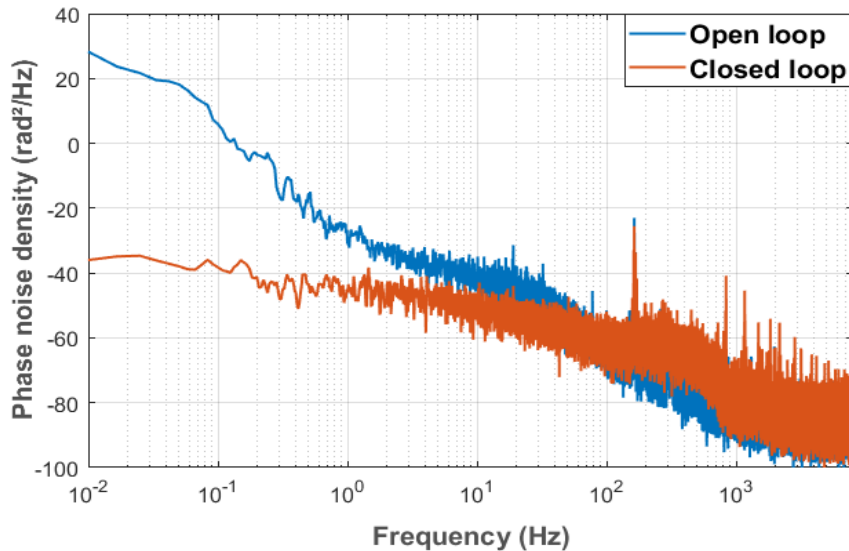


Figure. 5. Phase noise spectral density for open and closed loops in linear regime at a repetition rate of 55 MHz.

### 3. CONCLUSION AND OUTLOOK

We have demonstrated the first coherent combination of 60 LMA fiber amplifiers in the femtosecond regime using an interferometric method. This represents the highest number of coherently combined fiber amplifiers in the femtosecond regime, paving the way for a new generation of joule-class fiber lasers operating in the kW regime.

The next step of this work consists in the activation of the missing channel, and operating the laser at various powers (up to about half a kW of combined average power) and nonlinearity levels (B integral from 3 to 5 radians) and studying how these nonlinear effects might have an impact on the temporal and spectral beam profile or the coherent combination efficiency. One important issue to be addressed at this stage of the XCAN project is the thermal effect management especially when the laser system is operated at some kW of combined average power.

### 4. ACKNOWLEDGEMENT

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