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# Highly Scalable Coherent Beam Combining of Femtosecond Fiber Chirped-Pulse Amplifiers

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**Abstract:** We report on the coherent beam combining of seven fiber chirped-pulse amplifiers using a highly scalable architecture. A combining efficiency of 48% is obtained in linear regime, yielding 71 W pump-limited average power after compression, with a phase noise between two fibers as low as  $\lambda/38$  RMS. The experiment is operated at high  $B$ -integral, with only little impact on the combining efficiency as well as on the temporal and spatial properties of the combined beam.

**OCIS codes:** (140.3298) Laser beam combining; (140.3510) Lasers, fiber; (140.7090) Ultrafast lasers.

## 1. Introduction

For the last years, Coherent Beam Combining (CBC) has been widely used in femtosecond fiber chirped-pulse amplification architectures in order to scale the output pulse energy while preserving a good temporal quality. Several architectures such as tiled-aperture or filled-aperture, along with various phase measurement and control methods as LOCSET [1,2] or Hänsch-Couillaud [3], have been employed with a moderate number of fibers and demonstrated the high potential of CBC in the femtosecond regime. Record energies have been demonstrated up to the 10 mJ level [1], one order of magnitude above the energy accessible with one single emitter.

However, high-field experiments such as particle acceleration would take benefit of both high pulse repetition rates and high pulse energies at the Joule level. Thus, highly scalable CBC architectures need to be investigated. In this contribution, we report on a highly scalable CBC architecture of seven fiber chirped-pulse amplifiers operating at high power and high energy. It relies on a tiled-aperture geometry capable of easily stacking a very large number of fibers, along with an interferometric phase measurement method which is theoretically able to address up to 10.000 emitters using one single camera [4]. This proof-of-principle experiment paves the way to a further scaled CBC system involving 61 emitters.

## 2. Experimental setup

The experimental setup starts with a femtosecond oscillator delivering 200 fs pulses, centered at 1030 nm, at 55 MHz repetition rate. It is followed by a pulse picker allowing to reduce the pulse repetition rate, a 500 ps Chirped-Fiber Bragg Grating used for chirped-pulse amplification and a pulse-shaper. The beam is then split into eight channels, seven of which are used for the beam combining. These seven sub-beams are seeded through variable optical delay lines in free-space followed by piezo-driven fiber stretchers allowing to match the delay and the phase between the pulses, respectively. A second pulse picker stage allows for a further reduction of the pulse repetition rate down to 2 MHz. The output beams are pre-amplified in large-mode area core-pumped ytterbium-doped fiber amplifiers before seeding seven power amplifiers of 30- $\mu$ m mode-field diameter generating 25 W average power each. The fiber outputs are then stacked into a hexagonal array and individually collimated by a hexagonal microlens array. The common image focal plane represents the tiled-aperture and defines the near field of the global beam. The combined beam is directly found in the far field, obtained in the image focal plane of a lens. Hence, no combining elements are needed.

The phase measurement and control is performed by an interferometric measurement described in our previous work [4]. The near-field is imaged onto a 1 kfps camera along with a reference plane wave, derived from the eighth unused channel. The seven generated interference fringes patterns allow to measure the phase of each fiber relatively to the common reference and to act on the fiber stretchers with a kHz feedback loop in order to stabilize the relative phases in real time. The far field (see fig. 1) consists of one powerful central lobe surrounded by several side lobes which arise due to the periodic intensity distribution of the near field. The combined beam is selected by spatially

filtering the far field at its first zero. Finally, a grating compressor allows to recover the initial pulse duration of the combined beam.

### 3. Experimental results

The system is first operated in linear regime at 55 MHz repetition rate. The residual phase noise between two fibers exhibits a reduction of the low frequency noise of more than five orders of magnitude and a phase stability of  $\lambda/38$  RMS. We obtain a far field as shown in fig. 1 (left). After spatial filtering, the average power of the combined beam is measured to be 84 W, corresponding to a combining efficiency of 48 %. The combined beam is then spatially characterized using the second moment method and exhibits an  $M^2$  of 1.10 on both axis. After temporal compression, the output average power is measured to be 71 W, corresponding to a compression efficiency of 85%. At last, we measure a compressed pulse duration of 228 fs using a D-scan procedure, which is nearly Fourier-transform limited considering the spectrum shape of 9.7 nm FWHM. The corresponding autocorrelation function is shown in fig. 1 (right).

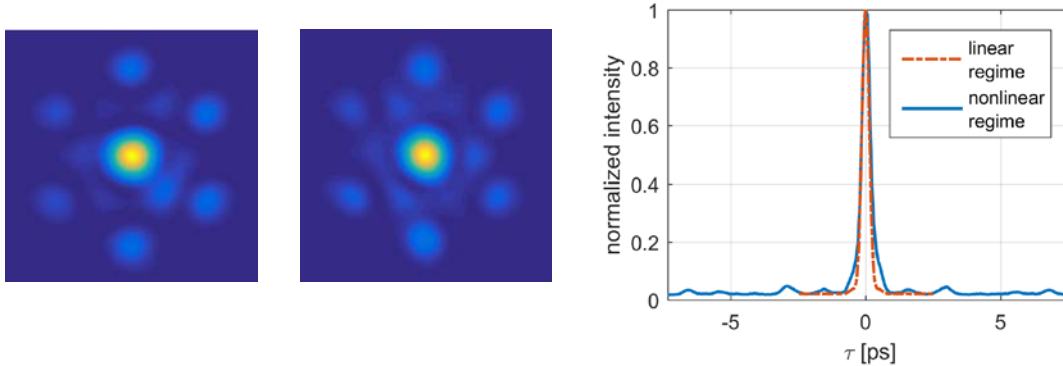


Fig 1: (left) Far field pattern in linear regime, (center) far field pattern in nonlinear regime, (right) Autocorrelation functions of the combined, compressed beams for both regimes.

Then, the pulse peak power is increased by reducing the repetition rate down to 2 MHz and keeping the output power constant. The  $B$ -integral from self-phase modulation that arises in the power amplifiers is estimated to 5 rad. If this nonlinear phase was the same for all amplifiers, it would have no impact on the combining efficiency. However, small discrepancies in input and pump powers between the seven power amplifiers and variations between the amplifying fiber lengths lead to slight  $B$ -integral mismatches between the channels which affect the far-field pattern, as shown in fig. 1 (center). Nevertheless, the filtered combined beam remains at 79 W, yielding a combining efficiency of 45 %. Due to the spatial filtering, the beam properties are not modified and preserve the same quality as in linear regime. The pulses are recompressed to 248 fs with a distorted temporal profile and exhibit side lobes inherent to self-phase modulation, as can be seen in the measured autocorrelation trace (fig 1 (right)).

### 4. Conclusion and outlooks

In conclusion, we demonstrated the highly scalable CBC of seven fiber chirped-pulse amplifiers operating at high average power both in linear and nonlinear regime at 48% and 45% efficiency, respectively. The combined beam exhibits good spatial properties and the pulse temporal characteristics are well preserved. Our CBC setup is ready to be scaled to 61 emitters with very little modifications to the current implementation, and paves the way to architectures involving a very large number of fibers to combine without drastically increasing the setup complexity.

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