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Review

Divided-pulse amplification for terawatt-class fiber lasers

T. Eidam[1,2,a], M. Kienel[1,2], A. Klenke[1,2], J. Limpert[1,2], and A. Tünnermann[1,2,3]

[1] Institute of Applied Physics, Abbe Center of Photonics, Friedrich-Schiller-Universität Jena, Albert-Einstein-Str. 15, 07745 Jena, Germany
[2] Helmholtz-Institute Jena, Fröbelstieg 3, 07743 Jena, Germany
[3] Fraunhofer Institute for Applied Optics and Precision Engineering, Albert-Einstein-Str. 7, 07745 Jena, Germany

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Abstract. The coherent combination of ultra short laser pulses is a promising approach for scaling the average and peak power of ultrafast lasers. Fiber lasers and amplifiers are especially suited for this technique due to their simple singe-pass setups that can be easily parallelized. Here we propose the combination of the well-known approach of spatially separated amplification with the technique of divided-pulse amplification, i.e. an additionally performed temporally separated amplification. With the help of this multidimensional pulse stacking, laser systems come into reach capable of emitting 10's of joules of energy at multi-kW average powers that simultaneously employ a manageable number of fibers.

1 Introduction

Fiber lasers and amplifiers possess an excellent reputation regarding their average power capability, their emitted fundamental-mode beam quality and their high efficiency. Therefore, in recent years they more and more evolved into the dominating solid-state-laser concept for many industrial and scientific applications. However, in terms of pulse energy and peak power they still lack orders of magnitude behind state-of-the-art bulk lasers that are nowadays capable of emitting peak powers beyond 1 PW. The reason for this restriction of fiber lasers is the propagation of the signal in small cores over long distances and the related occurrence of nonlinear pulse distortions and optically induced damage.

The main goal followed within the International Coherent Amplifying Network (ICAN) project is to combine the immense peak power today only bulk systems can deliver with all the advantages of the fiber technology, i.e. average power, efficiency and beam quality. The impact of such a laser system on ambitious applications such as laser-wakefield acceleration [1] would be enormous.

[a] e-mail: eidam.tino@uni-jena.de

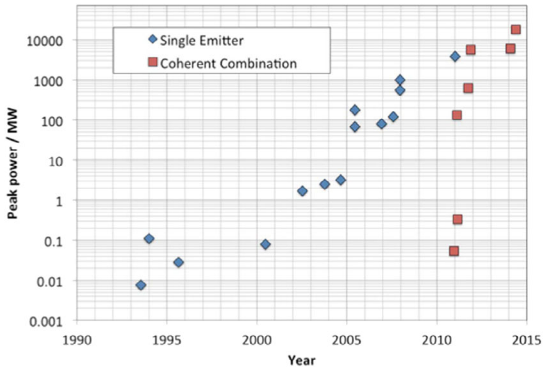

Fig. 1. Peakpower evolution of ultrafast fiber lasers in the last 25 years for both single-emitter system and systems using coherent combination.

Now, the idea is to exploit a further advantage of fiber technology: the simple high-gain single-pass setups that allow for an easy parallelization. Thus, before amplification the laser pulses can be spatially separated into N parallel channels, amplified in each channel until the individual limitations are reached, and, finally, coherently combined into one single beam. Thus, assuming a lossless combination, an increase in peak and average power by a factor of N is possible. This technique, initially employed for continuous-wave lasers [2], has recently been successfully demonstrated for ultrafast lasers [3] and has led to laser systems that today already outperform the single-emitter counterparts [4,5].

Figure 1 shows the peak-power evolution of fiber-based system during the last years. It can be clearly seen that the technique of coherent combining allowed for continuing the path (approximately 3 orders of magnitude every decade) that has been followed with single-emitter system in the last years. Thus, the current peak power record is held by fiber-based system combining three channels to a peak power of 18 GW [6].

However, achieving pulse energies of 10's of joules as it is targeted within ICAN is not a realistic scenario when using only parallel amplification. The huge number of required channels (thousand or even millions) and the related costs would not allow for a realization. Thus, the idea described within this paper is to add a further dimension to the pulse combining: the temporal pulse division and combination.

2 Divided-pulse amplification

The technique of temporal pulse splitting, amplification and subsequent combination has been known for a few years [7–9] and usually referred to as divided-pulse amplification (DPA). In order to employ DPA in addition to chirped-pulse amplification (CPA), i.e. to introduce a temporal delay long enough to separate pulses that are stretched to nanosecond duration, free-space delay lines in combination with polarization beamsplitters (PBS) have to be used. A typical DPA setup is depicted in Fig. 2. After the front end, the pulses are split into four replicas in a splitting stage using two delay lines. Each delay line consists of a half-wave plate (HWP) that is used to control the incident polarization and, therewith, the splitting ratio. Afterwards, the pulse is split with a PBS, i.e. its p-polarized part is transmitted and its s-polarized part is delayed in a double-pass delay line employing two quarter-wave plates (QWPs). The four replicas are amplified and, finally, recombined in a combining stage with a setup symmetric to the division stage. Since this is an interferometric setup, the phase in

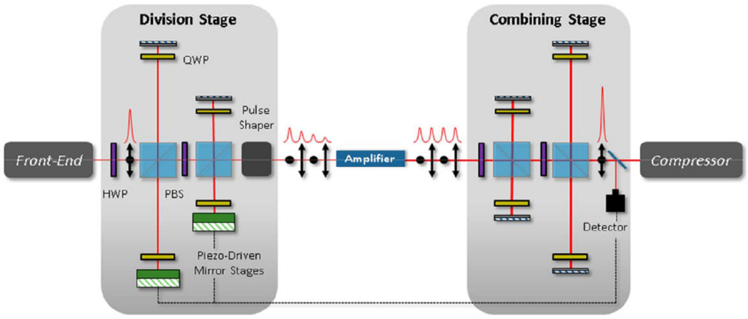

Fig. 2. Schematic setup of an actively stabilized DPA setup. In the depicted case, four pulse replicas are generated with two delay lines, amplified and, finally, recombined. The black dots and arrows denote the state of polarization of each replica. QWP: quarter-wave plate, HWP: half-wave plate, PBS: polarization beam splitter.

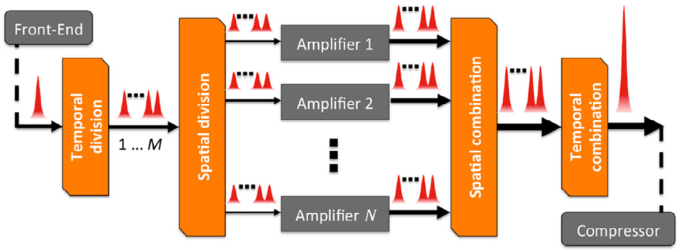

Fig. 3. Schematic setup of a CPA system employing both temporally and spatially separated amplification and coherent combination before compression.

each delay line has to be controlled via an active stabilization measuring the state of polarization of the combined pulse with an Hänsch-Couillaud detector [10] and controlling the phase via a feedback loop and two piezo-mounted mirrors. After the combining stage, the pulses are compressed back to femtosecond durations.

This actively-controlled setup brings the advantage of controlling the amplitude of the pulse train before the amplifier. Thus, with an increased number of degrees of freedom saturation effects that would hinder an efficient recombination in a passive setup (i.e. the same stage is used for division and combination [11,12]) can be compensated for. Thus, with this technique, ultra-short mJ-level pulses exceeding single-pulse limitations could already be demonstrated [13].

3 System design for a terawatt-class fiber laser

The next important step is, of course, to combine both techniques, i.e. spatially separated and temporally separated amplification, into one single setup. Figure 3 depicts the systematic setup of such a system.

In the ideal case of a lossless combination, the peak power of a single-pulse system could be increased by a factor of $N \cdot M$ assuming a division into N spatially separated channels and M temporally separated pulse replicas. Furthermore, Fig. 4 shows a proposed setup for a 1 J pulse energy and 3 TW peak power laser system emitting at a repetition rate of 15 kHz, i.e. at an average power of 15 kW. Of course, these unprecedented laser parameters come with the known advantages of fiber-based systems, i.e. with high efficiency and an excellent beam quality.

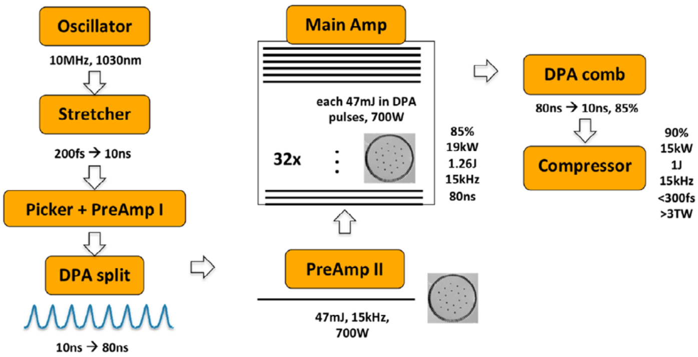

Fig. 4. Proposal for a terawatt-class fiber laser emitting at 15 kW average power.

As front-end a standard oscillator is employed emitting femtosecond pulses at 10 MHz repetition rate and at 1030 nm central wavelength. These pulses are stretched to 10 ns duration in a grating-based stretcher, pre-amplified and picked down to the desired repetition frequency of 15 kHz. A temporal DPA splitting into eight replicas is assumed (i.e. 3 delay lines) corresponding to an effective stretched pulse duration of 80 ns. As amplifying fibers both in the second pre-amplifier and in each channel of the main amplifier large-mode-area large-pitch fibers (LPFs [14]) are employed. In the proposed system these fibers are able to emit a pulse train of 47 mJ total energy at an average power of 700 W. Although this average-power is roughly a factor of two above state-of-the-art parameters, we are confident that this can be achieved with the next generation of large-mode-area LPFs. However, please note that in this approach the same parameters can be achieved just by decreasing the requirements for each channel and by increasing simultaneously the number of channels.

In front of the main amplifier the pulses are spatially split into 32 channels either with a cascaded PBS setup or a 1:32 beam splitter (e.g. a diffractive-optical element). After amplification and spatial combination a total energy of 1.26 J and an average power of 19 kW is achieved. Finally, assuming a DPA-combination efficiency of 85% and a compression efficiency of 90%, an energy at the system output of 1 J (i.e. >3 TW at 300 fs pulse duration) at an average power of 15 kW is reached.

Of course, this proposed system will pose many challenges before it can be realized such as the simultaneous handling of both high peak powers and high average powers, an efficient temporal and spatial combination at this channel count, etc. However, in our opinion, these issues can be solved with steady improvements in technologies already available today and that there are no fundamental physical limitations hindering the achievement of these parameters. Therefore, we are convinced that the approach presented herein is the most realistic scenario to achieve even the ambitious laser parameters as discussed within the ICAN project.

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