ADVANCED SOLID-STATE LASERS ARE MERGING WITH ACCELERATORS

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Abstract

In recent years, lasers have been developed to an essential tool in accelerator science for a variety of uses, ranging from the production and manipulation of electron beams to novel acceleration techniques and advanced light sources. These applications in accelerator science require for advanced high average high peak power lasers as pointed out most recently by ICFA (The International Committee for Future Accelerators); ICUIL (The International Committee on Ultra-High Intensity Lasers); ICAN (International Coherent Amplifier Network) and IZEST (International Zeta-Exa-Watt Science and Technology). However, lasers are known as sophisticated systems with a notorious poor efficiency. Most recently, rare-earth-doped fibers have established themselves as an attractive and power scalable solid-state laser concept. Using advanced large-mode-area fibers, in continuous-wave operation output powers in the 10 kW-regime with diffraction-limited beam quality at electrical to optical efficiencies of 30 percent have been demonstrated. In the pulsed regime average powers of the order of 1 kW even for femtosecond fiber laser systems have been reported. Coherent beam combination of these lasers allows for the generation of high peak power pulses at high repetition rates and output powers. In this contribution the state of the art in solid-state laser technology operating at high average powers with inherent high efficiencies is reviewed. The prospects for future developments that will meet the demands set by the accelerator community will be discussed.

INTRODUCTION

Undoubtedly, the laser parameters required for realizing next-generation laser-plasma accelerators are extremely challenging for every laser architecture. Typically, these accelerators will consist of several stages with each stage capable of producing femtosecond pulses with an excellent beam quality, several Joules of pulse energy and, what is most demanding, an average power of several hundred kilowatts [1] – similar specifications are needed for advanced light sources. Additionally, the wall-plug efficiency should be as high as possible regarding the otherwise immense power consumption of the accelerator facility.

From today's point of view, these laser requirements cannot be achieved with a single-emitter system and, consequently, the coherent combination of several (possibly thousands or even more) emitters will be necessary. For this approach, fiber laser and amplifiers are a promising source due to their high efficiencies, their excellent power-handling capabilities and the possibility to realize compact and monolithic setups.

A first way to achieve the required parameters is to coherently combine many (possibly millions) small-core fiber systems [2]. However, the realization of such a concept comes with a large number of problems to solve, such as its immense component count and the related costs, the necessary alignment, etc. Another, in our opinion more realistic scenario, is to combine a smaller number of large-mode-area fibers. Furthermore, the total number of sub-systems can be decreased by employing passive cavities for pulse stacking, as it will be discussed at the end of the paper. The paper is organized in the following way: After describing state-of-the-art single-emitter systems in Sec. 2, the idea of coherently combine ultrashort pulses is introduced in Sec. 3. In Sec. 4 the proposed concept of pulse stacking is described and, finally, a conclusion is given in Sec. 5.

ULTRAFAST FIBER AMPLIFIERS

In recent years, there has been a tremendous increase of peak power and average power of ultrafast fiber amplifiers. This progress became possible by steady developments both in chirped-pulse amplification (CPA) technology and in novel large-mode-area fibers. In principle, it is desirable to use single-mode fibers for the amplification with a minimal length and a maximum mode-field diameter. Unfortunately, due to production tolerances strictly single-mode behavior can only be achieved using step-index fibers with a maximum core diameter of 13 µm. For a further area increase, other guiding mechanisms have to be used, e.g. the

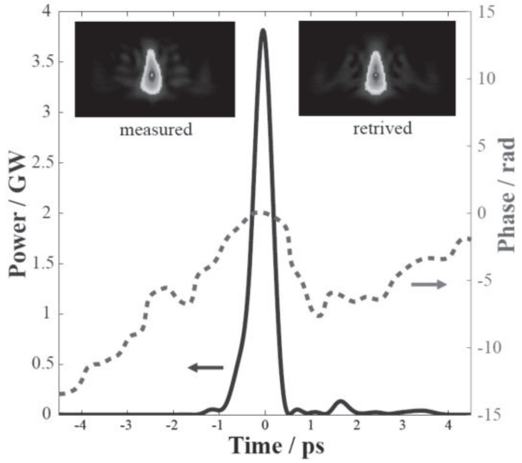

Figure 1: FROG measurement at a maximum achieved energy of 2.2 mJ and 480 fs pulse duration.

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delocalization of higher-order modes in so-called large-pitch fibers (LPFs) [3], which are a subcategory of photonic-crystal fibers (PCFs). Thus, by using a short-length LPF with a large signal core diameter of 100 µm 480 fs long pulses with 2.2 mJ pulse energy and 3.8 GW peak power could be realized [4]. The corresponding pulse shape is depicted in Fig. 1. The LPF employed in the main amplifier is depicted in Fig. 2. For comparison, a standard fiber with 6 µm core and 128 µm cladding diameter, a rod-type fiber with 85 µm core and 200 µm air-clad diameter are shown. This picture shows the impressive core size increase and the related intensity reduction during signal propagation and the corresponding mitigation of detrimental nonlinear effects.

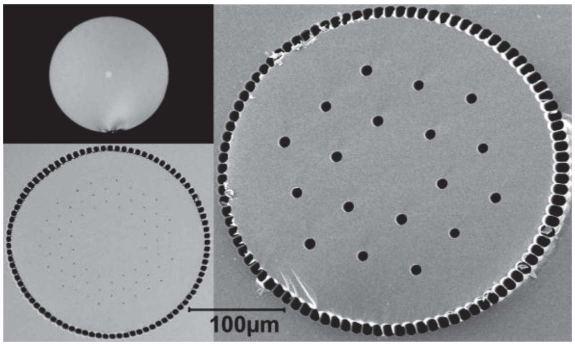

Figure 2: Microscope images (all at the same scale) for a standard fiber with 6 µm core and 128 µm cladding diameter (upper left), of a rod-type fiber with 85 µm core and 200 µm air-clad diameters (lower left). On the right the LPF employed in the high-peak power experiment is shown.

A record average power of 830 W in the femtosecond regime could be achieved by using a similar CPA system with a longer step-index fiber possessing a mode-field diameter of 27 µm [5]. The corresponding output slope of the system is shown in Fig. 3.

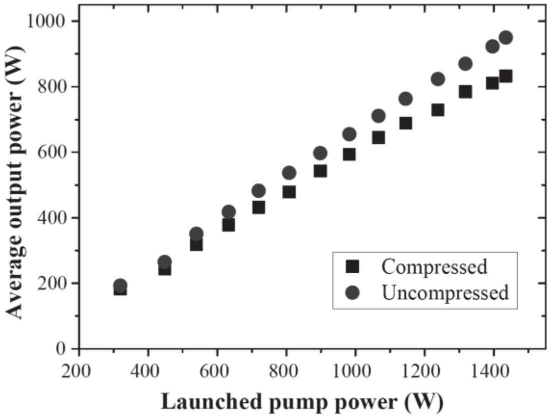

Figure 3: Compressed and uncompressed average output power of the femtosecond CPA system.

In this case the pulse energy was restricted to 10.6 µJ due to the small core size.

Of course, it is a challenge to combine these two record parameters in one fiber CPA system, since the employed fibers (on the one hand a 1.2 m long LPF with a large core in order to increase nonlinear pulse distortions and, on the other hand, an 8 m long step-index fiber optimized for single-mode operation under strong heat load) are extremely different. However, by slightly reducing the core size of the LPF, it is possible to simultaneously achieve mJ-level pulses at average powers of several hundred watts.

COHERENT COMBINING

The concept of coherent combination can be included into an existing CPA system by splitting the pulses into N channels after the pulse stretcher, amplifing each channel in a separate fiber and, finally, combining the pulses before compression (see Fig. 4). Since this is an interferometric setup, the path lengths have to be stabilized. This way, the achieved average and peak power of a CPA system can be increased a factor of N (neglecting additional losses in the combining element).

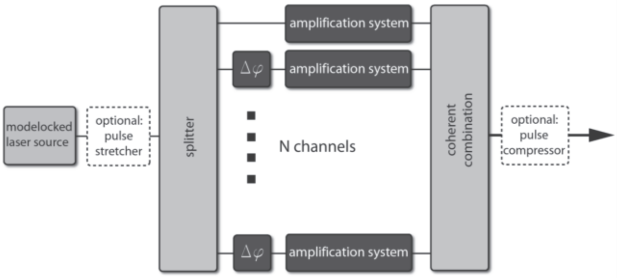

Figure 4: Schematic setup of a CPA system employing the splitting and subsequent combination of N channels.

So far, power values exceeding those of single-emitters could be demonstrated by using a two-channel system that employs polarization beam splitters for splitting and combining [6]. In this experiment, pulses with 3 mJ energy, 460 fs duration and 5.4 GW peak power has been produced for the first time in a fiber-based CPA system.

When optimizing the coherent combination of ultrashort pulses, additional effects have to be considered compared to coherent combination in the continuous wave regime. Those include, but are not limited to temporal delays, dispersion and non-linear effects. It turns out that the temporal delay between pulses is a critical aspect to maintain a high combining efficiency and going to shorter pulse lengths results in quite stringent requirements for the maximum temporal delay. For pulse durations of 100 fs, corresponding to a bandwidth of about 15 nm at 1 µm wavelength, the delay between the pulses will have to be kept below about 10 wavelengths. However, when scaling from the combination of two channels to a larger number of channels, the figure of merit will converge to a constant value. Hence, the loss of efficiency for the total system can be kept reasonable small. The same conclusion applies to mismatches of the dispersion and the B-integral. If the fiber length differences can be kept below a value of about 1 cm, and the B-integral differences are smaller than 0.5 rad, the figure of merit for a total system with a large number of channels is still very high.

PULSE STACKING

The demand for a huge number (i.e. up to millions) of channels for a fiber-based particle accelerator with the parameters discussed above comes only from the energy limitation of the fibers and not from the achievable average power. Therefore, it is possible to reduce the required number of channels by 2-3 orders of magnitude by operating the fiber amplifiers in burst mode and by including enhancement cavities in the systems. With the help of these cavities, the pulses within one burst can be coherently overlapped and the resulting high-energy pulse can be coupled out of the cavity via a fast switching element. The schematic representation of this idea is shown in Fig. 5.

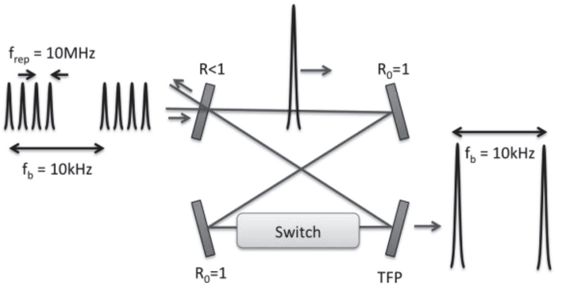

Figure 5: 10 MHz pulses emitted in a burst with 10 kHz repetition frequency are stacked in a passive cavity and coupled out employing a fast switch.

In case of an ideal switching element, i.e. in case of negligible losses, the pulse energy is increased by simultaneously reducing the repetition frequency at a constant average power. Although the average-power scaling of such cavities to tens of kilowatts has already been demonstrated [7], novel switching elements have to be identified, since the efficiency of the cavity strongly depends on the round-trip losses.

Finally, the incorporation of these cavities in a CPA system that already employs coherent combing, i.e. a spatial and a temporal pulse-energy addition, could result in impressive power values with a manageable number of individual channels. A schematic setup of such a possible system based on (only) 160 large-mode-area fibers is shown in Fig. 4, which will should allow to reach and even to cross the Terawatt level with fiber laser technology for the first time.

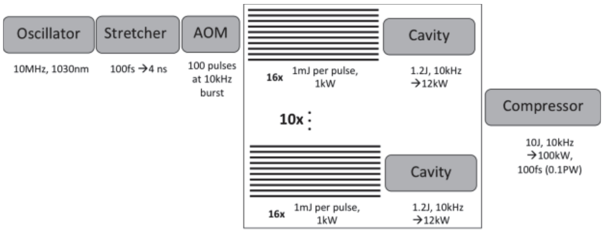

Figure 6: Schematic setup of a “table-top” fiber-based CPA system capable of generating femtosecond pulse with a peak power of 0.1 PW and 100 kW of average power.

CONCLUSION

In conclusion, ultrafast solid-state lasers and especially fiber lasers have become an interesting source for laser-based particle acceleration and the development of advanced light sources. They open up a completely new parameter space, which is and will be inaccessible for Ti:Sa systems with their extremely low efficiencies and average-power limitations.

By using fiber amplifiers and employing both coherent combining and pulse stacking in a passive enhancement cavity, impressive laser parameters (hundreds of kilowatts of average power and peak powers <1 TW) come into reach for the first time.

ACKNOWLEDGEMENT

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