# Trends in high-power ultrafast lasers

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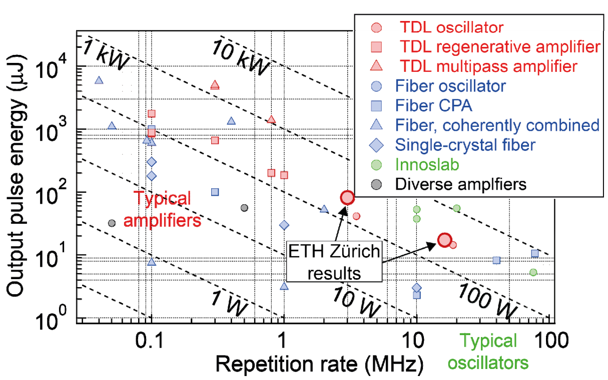
## ABSTRACT

Ultrafast laser sources are one of the main achievements of the past decades. Finding new avenues to obtain higher average powers and pulse energies from these sources is currently a topic of important research efforts both for scientific and industrial applications. SESAM modelocked thin-disk lasers are one of the most promising laser technology to reach this goal from table-top systems: recently, average powers of 275 W and pulse energies of 80 μJ were demonstrated directly from a modelocked oscillators without additional external amplification. In this presentation, we will review the current state-of-the art of such table-top systems and present guidelines for future kilowatt-class systems.

**Keywords:** High-power lasers, thin-disk lasers, ultrafast lasers, modelocking, semiconductor saturable absorber mirror

## 1. INTRODUCTION

In the last few decades, ultrafast lasers have become the main workhorse in many fields in science and technology. Nowadays, increasing needs for faster acquisition times and higher yields are boosting demands for ultrafast laser sources with ever-increasing average power, i.e. ultrafast laser sources that combine high peak power (in the tens to hundreds of megawatts) and high repetition rate (in the megahertz regime). The resulting lasers with hundreds to thousands of watts of average power, open up many new applications. One important example in science is the field of strong-field physics, for example high-harmonic generation or attosecond science [1]. Another prominent application field, is the need in industry for high-speed and high-precision micromachining of a wide variety of materials including metals, glasses and semiconductors [2]. The increasing speed of available scanners now justifies the use of laser systems with very high repetition rates in the MHz regime.



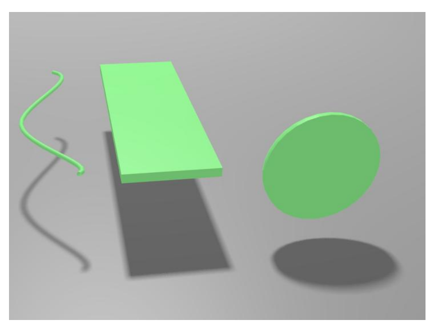



Figure 1. a) State-of-the-art of high-power ultrafast laser systems. Different technologies have been pushing the average power frontiers, recently surpassing the kilowatt milestone. b) illustration of different laser geometries suitable for high-power lasers (fibers, slabs, disks).

In recent years, high-power ultrafast laser systems have made very large progress, currently surpassing the kilowatt average power milestone. The main drivers of this progress have been diode-pumped solid-state laser technologies, mostly based on amplifier schemes using Yb-doped materials as gain media. The common point between all these technologies, (fiber, slab and disk) is the outstanding cooling geometry of the gain medium, which is suitable for average power scaling. Among these laser geometries, the thin disk concept is ideally suited for short pulses as it combines amplification with small interaction volume, therefore both nonlinearities and thermal distortions are minimized (Fig. 2a)

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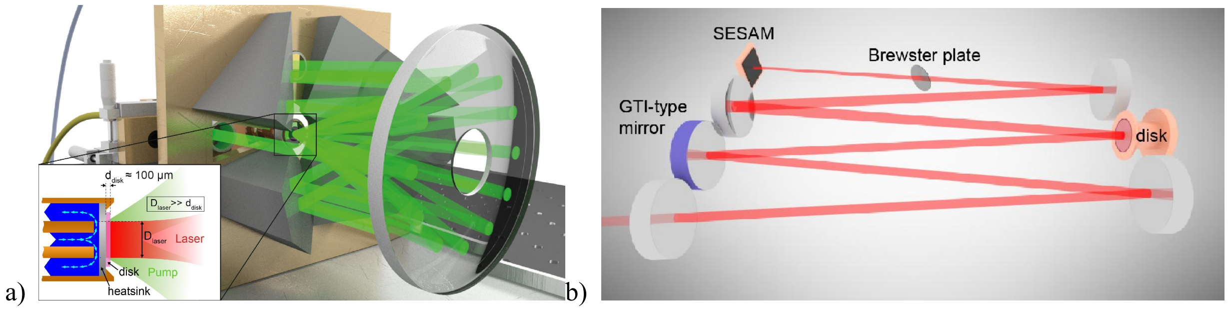


Figure 2 a) Illustration of thin-disk multi-pass pumping scheme b) Typical layout of SESAM modelocked thin-disk laser

The use of thin disk technology for power scaling of ultrafast sources, both mode-locked oscillators and amplifiers, has gained significant ground in the past few years. Passively mode-locked thin-disk lasers (TDLs) [3] using SEmiconsductor Saturable Absorber Mirrors (SESAMs) [4] are an elegant option to reach the desired levels in table-top systems, as unprecedented high pulse energy and average power levels can be reached at MHz repetition rate directly from a passively mode-locked oscillator without any extra amplification (Fig. 2b). This approach has many potential advantages compared to amplifier systems with similar performance: for example in terms of reliability, long-term stability and complexity. Since their first demonstration in the year 2000 at ETH Zürich, mode-locked TDLs have outperformed other types of ultrafast oscillators in terms of output average power and pulse energy and a steady increase in the achievable levels illustrates the potential for further scaling (Figure 3).

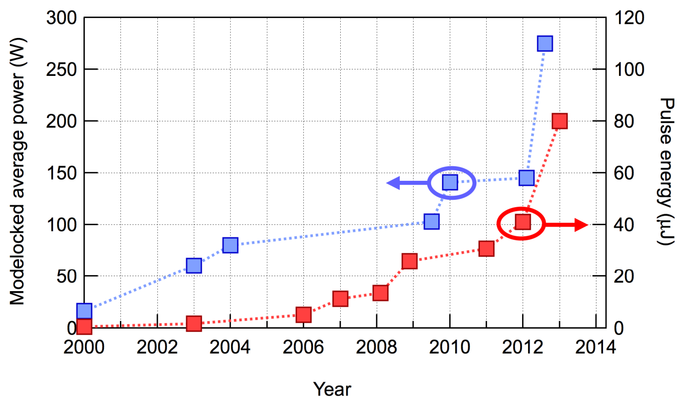


Figure 3. Evolution of average power and pulse energy of modelocked thin-disk oscillators since their first demonstration in the year 2000

In this presentation, we will give an overview of the state-of-the-art of high-power ultrafast laser systems with a focus on compact systems based on modelocked thin-disk lasers. We will present an overview of the state-of-the-art, as well as current trends for scaling of future systems, in particular with novel laser gain materials and optimized components.

## 2. FRONTIERS IN AVERAGE POWER AND PULSE ENERGY OF MODELOCKED THIN DISK LASERS

### 2.1 High power and high energy modelocked thin disk lasers

The highest average power reported from an Yb:YAG TDL is 275 W with 583-fs long pulses at a pulse energy of 17 µJ [5]. In terms of pulse energy, we were able to push this performance to a new regime with the demonstration of a pulse energy of 80 µJ in 1.07 ps pulses at a repetition rate of 3.03 MHz corresponding to an average power of 242 W [6]. A schematic of these record holding systems is given in Figure 4.

SESAM-modelocked TDLs operate in the soliton modelocking regime [7, 8]. This means a careful balance between nonlinear phase (due to self-phase modulation) and negative group-delay dispersion needs to be achieved within one round-trip of the laser pulses in the laser resonator. For power and energy scaling, careful design guidelines need to be followed to avoid excessive nonlinearities and maintain stable modelocking. In order to reach both a high pulse energy and high average power, we operate our modelocked oscillators in a vacuum environment to minimize the parasitic nonlinearity caused by the air inside the oscillator.

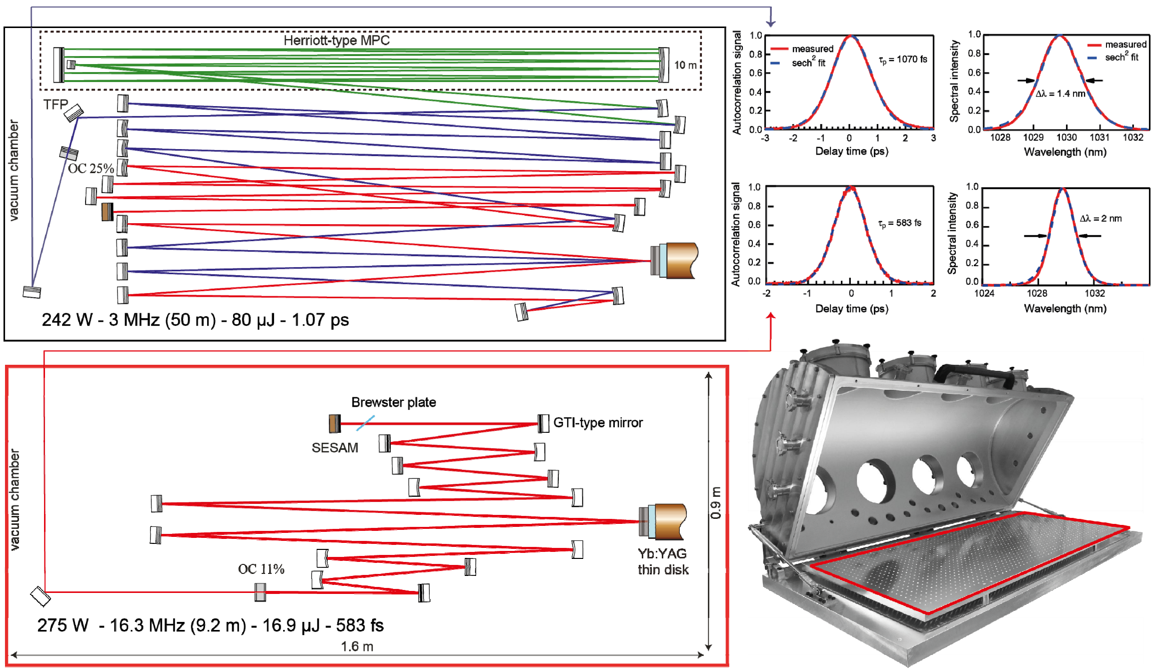


Figure 4 a) Layout of current record holding modelocked TDLs b) Autocorrelation and optical spectrum of the pulses showing clean soliton pulses c) picture of the vacuum chamber in which the laser was operated to reduce the parasitic air nonlinearity in the resonator.

## 2.2 SESAMs for high power oscillators

SESAMs are critical components to achieve stable modelocked operation. In the particular case of modelocked TDLs all intracavity elements are pushed into extreme conditions and SESAMs must be designed and fabricated accordingly. We provided guidelines for a significant increase of the damage threshold of these non-linear reflectors in a recent study [9]. In particular, anti-resonant designs with multiple quantum wells (QWs) saturable absorber layers and dielectric top coatings, showed to be key to improve the damage threshold by several orders of magnitude. In addition, we demonstrated that these high-power SESAMs can be processed after epitaxial growth with substrate removal and heatsinks with better thermal conductivity and superior surface flatness [10] (Figure 5).

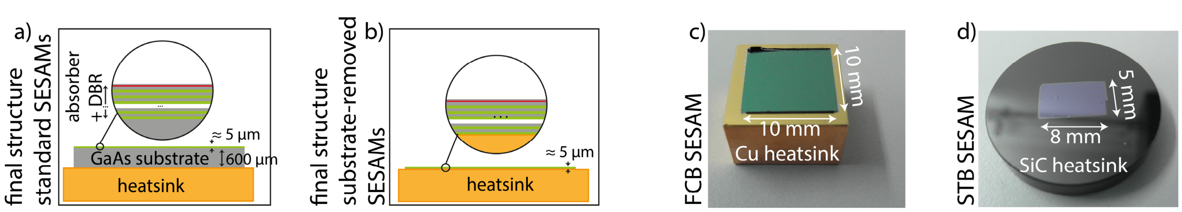


Figure 5 a,b) Schematics processed structures of standard SESAMs and substrate-removed SESAMs. c) Photographs of substrate removed SESAMs using different techniques We demonstrated different substrate removal techniques: (1) upside-down (USD) grown SESAM, i.e. with the absorber layer grown before the distributed Bragg reflector (DBR), that is flip-chip bonded onto a Cu substrate (2) right-side up (RSU) grown SESAM (i.e. DBR growth followed by the low-temperature grown absorber) mounted on a super-polished SiC substrate. This latter sample is fabricated using a proprietary crystalline coating process developed by Crystalline Mirror Solutions (CMS) [11].

We believe these improved SESAMs will be a key-enabling component for further power and energy scaling of high-power ultrafast oscillators.

## 3. SCALING THE PULSE DURATION OF MODELOCKED THIN DISK LASERS

### 3.1 New materials for high-power modelocked thin-disk lasers

The outstanding performance of modelocked TDLs paves the way towards compact oscillator driven high-harmonic generation and attosecond pulse generation in the MHz repetition-rate regime allowing for reduced acquisition time and improved signal-to-noise ratio [1]. The required peak intensities for strong field applications are already reached by ultrafast TDLs, but typically at pulse durations of several hundred femtoseconds which represents an important limitation in most targeted experiments. However, the remaining challenge is to achieve pulse durations in the sub-100 fs regime directly from the oscillator in combination with high average power and high pulse energy, see Figure 6.

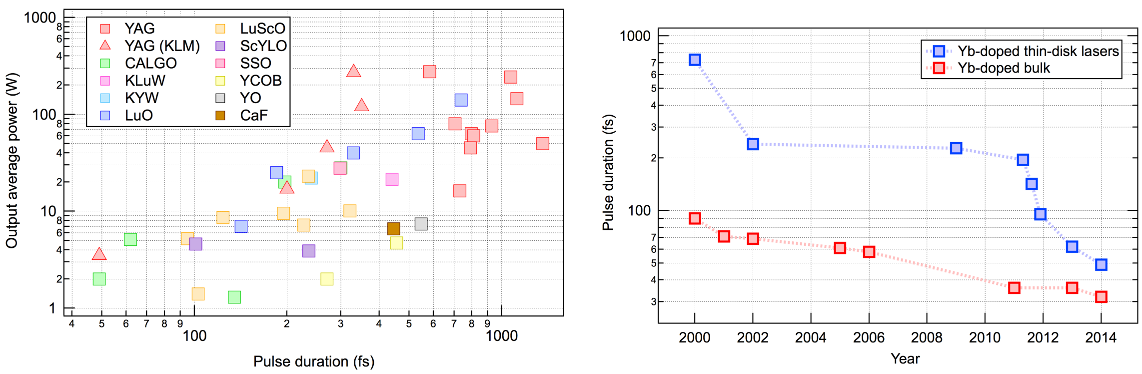


Figure 6 – a) Output average power of demonstrated modelocked TDLs based on different gain materials, showing the ongoing challenge of achieving short pulse durations and high average power levels b) Evolution of pulse duration available from modelocked thin disk lasers: reducing the pulse duration from state-of-the-art high-power systems represents one major milestone.

The fundamental requirements on gain materials for modelocked TDLs are a good thermal conductivity that allows for power scaling and a broad gain bandwidth that supports short pulse durations. These requirements are often contradictory: in order to obtain a broad gain bandwidth disordered crystals are typically used, that in turn exhibit poor thermal properties. The most promising gain material is Yb:$CaGdAlO_4$ (Yb:CALGO) that exhibits a broad FWHM emission bandwidth of 78 nm and a thermal conductivity of 6.9 $W \cdot m^{-1} \cdot K^{-1}$ similar to that of Yb:YAG at typical doping concentrations. The currently shortest pulses from a TDL with a duration of 62 fs at an average output power of 5.1 W are obtained from an oscillator based on this gain crystal [12]. In order to circumvent the reduced thermal conductivity of disordered broadband materials, an interesting alternative approach is the dual-gain concept that combines two gain materials with high thermal conductivity and shifted emission peaks in a single resonator. In modelocked operation, the two emission spectra combine to a single broad gain spectrum. We implemented this approach to the TDL geometry by combining the two pure sesquioxides Yb:$Lu_2O_3$ (Yb:LuO) with a center gain wavelength at 1034 nm and an emission bandwidth of 13 nm, and Yb:$Sc_2O_3$ (Yb:ScO) with a center gain wavelength at 1041 nm and an emission bandwidth of 12 nm [13].

We are confident that using both approaches, significantly higher power and shorter pulses can be achieved by improving the quality of the available gain disks and contacting to diamond heatsinks. Furthermore, ongoing work on fast SESAMs with high-damage threshold will support further progress in both configurations.

### 3.2 Pulse compression at high average power

An alternative approach to reduce the pulse duration of current record holding TDLs is to temporally compress the pulses using spectral broadening via self-phase modulation and subsequent compression. Efficient compression of TDLs combining high average power of hundreds of watts and high peak powers of tens of megawatts remained for long time a challenge. We have recently demonstrated that spectral broadening and pulse compression in gas-filled Kagome-type hollow-core-photonic crystal fibers (HC-PCFs) is ideal to reduce the pulse duration in the peak power range currently available from modelocked TDLs into the sub-100-fs range: their intrinsic guiding properties [14] enable an outstanding combination of extremely high damage threshold and low losses over wide transmission windows, which is further enhanced by the hypocycloid-shape of the hollow-core surround. Previously, we used a Xe-filled Kagome HC-PCF to reduce the pulse duration of a TDL from 860 fs down to sub-50 fs, with only a moderate pulse energy of 1.9 µJ and output power of 4.1 W [15]. More recently, pulse compression of mJ-level femtosecond pulses was demonstrated at moderate average output power (≈ 1 W) [16]. In our most recent results, we demonstrated that Kagome HC-PCFs are suitable for femtosecond pulse compression (and beam delivery) in the 100-watt average power regime [17]. In our experiment (Figure 7), the output of a TDL (127 W, 7 MHz, 18 µJ, 740 fs) was directly launched into a 13 bar Ar-filled Kagome-type HC-PCF, obtaining 88-fs pulses at 107 W of average power, and reaching over 85% overall compression efficiency and a peak power of 101 MW.

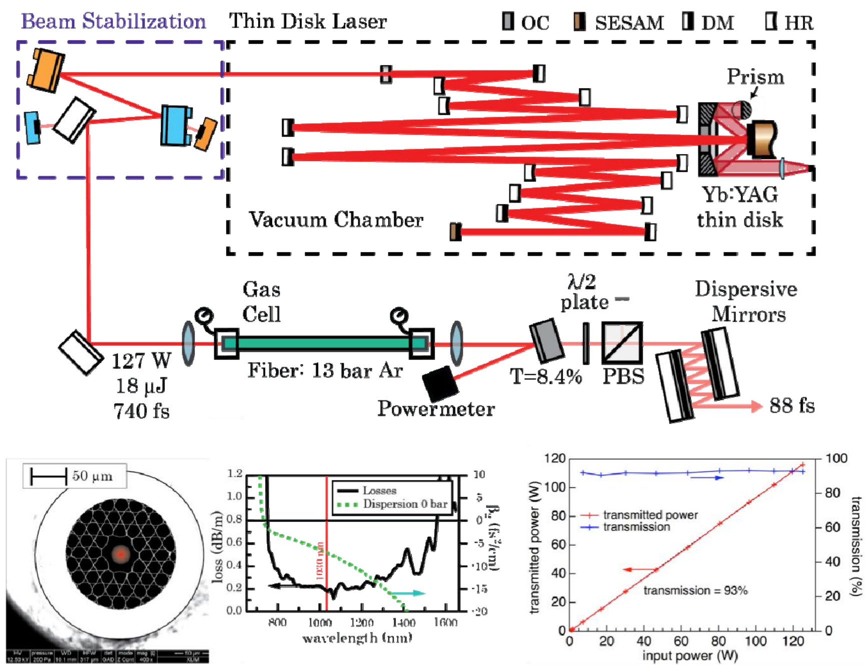


Figure 7 a) Experimental setup for the high average power pulse compression b) The low-loss 66 cm-long hypocycloid-core Kagome HC-PCF is hold in a gas chamber with 13 bar of Argon. The output is collimated and sent through a polarizing beam splitter (PBS) and a pair of dispersive mirrors c) The transmission through the fiber alone reaches up to 118 W of output average power (93% of transmitted power).

## 4. APPLICATION: HIGH HARMONIC GENERATION

One important application of these high-power ultrafast sources is for compact XUV sources at high repetition rate. Several applications would significantly benefit from such higher megahertz repetition rates, for example coincidence detection or surface science experiments. There has been significant progress in high-power ultrafast laser systems in recent years, which enabled numerous advances in the pursuit of high-repetition rate HHG (> 100 kHz) during the last decade. Using, for example, external HHG schemes with high power fiber amplifier systems or HHG inside enhancement cavities, several µW per harmonic have already been demonstrated at MHz repetition rate. This, however, usually comes at the expense of comparatively complex driving systems. Among the laser technologies reaching the required high pulse energy at high repetition rates for HHG, SESAM modelocked thin-disk lasers (TDLs) appear particularly promising as they have shown comparable performance than amplifier systems, directly from the output of a compact multi-megahertz laser oscillator [18].

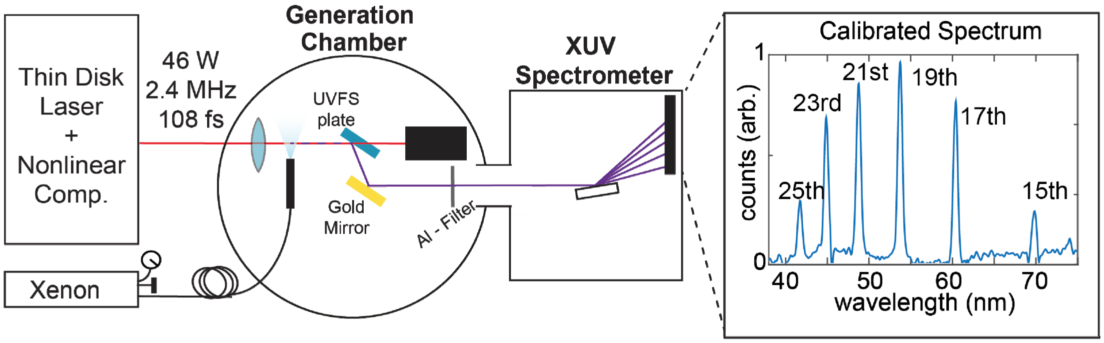


Figure 8. Figure captions are indented 5 spaces and justified. If you are familiar with Word styles, you can insert a field code called Seq figure which automatically numbers your figures.

We recently demonstrated a compact and simple setup for HHG driven by the compressed output of a TDL [19] (Figure 8) which provides IR driving pulses with 108 fs pulse duration at $\approx 5.5\text{x}10^{13}$ W/cm$^2$ of peak intensity and 2.4 MHz pulse repetition rate. In this first demonstration, we have achieved a total XUV flux of $>3\text{x}10^8$ photons/s in a single-pass over a Xe gas nozzle at 2.5 bar of backing pressure, which corresponds to a conversion efficiency of $>1.5\text{x}10^{-11}$.

Our compact XUV source based on HHG at 2.4 MHz repetition rate from the compressed output of a modelocked thin disk laser oscillator opens the path towards the next generation of compact high-repetition rate coherent XUV sources driven directly by low-noise passively modelocked diode-pumped solid-state laser oscillators.

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