Modelocked thin-disk lasers and their application for high-power THz generation

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ABSTRACT

Progress in the performance of high-power ultrafast lasers continues to give momentum to many fields of science and technology. Nowadays, ultrafast laser systems delivering hundreds of watts of average power with pulse energies ranging from hundreds of microjoules to hundreds of millijoules start to be even commercially available. In particular, disk lasers have consistently been at the forefront of this progress: their geometry is particularly well-suited for power and energy scaling of ultrashort pulses. Among these laser systems based on the disk technology, one particular technology is particularly attractive as a potential path to achieve the desired level from a simple, one-box, multi-MHz repetition rate oscillator: modelocked thin-disk oscillators can reach hundreds of watts of average power with femtosecond pulses at multi-MHz repetition rate. Exponential progress in the achievable levels is only an illustration of their enormous potential. So far, these oscillators reach up to 275 W average power, and pulse energies up to 80 µJ, both based on Yb:YAG thin-disk lasers. This talk will review latest progress achieved with this technology and next steps and challenges towards further scaling, as well as their prospect as compact driving sources for the generation of high-power THz radiation.

Keywords: high-power lasers, thin-disk lasers, modelocking, terahertz

1. INTRODUCTION

Recent progress in ultrafast laser technology at 1 µm wavelength has enabled to largely exceed the kilowatt average power level with picosecond and sub-picosecond pulses in various laser architectures (Fig. 1). Commercial solutions offering hundreds of watts of average power with sub-picosecond pulses have even become recently available. Three laser architectures are at the origin of this extremely fast progress: thin disk, fiber and slab lasers based on Yb-doped gain media. Most commonly, ultrafast laser systems capable of reaching hundreds of watts to kilowatts of power are based on amplification of a low power ultrafast oscillator, and the progress achieved in the last few years from ultrafast thin-disk oscillators and amplifiers has been particularly impressive. We focus here in more detail on this geometry, as it offers the unique possibility of developing very high-power oscillators directly. This stands in strong contrast with other geometries (fibers and slabs). Since their first demonstration in the year 2000 [1], mode-locked thin-disk oscillators have consistently achieved orders of magnitude higher average power and pulse energy than any other ultrafast oscillator technology, reaching comparable levels to advanced high-power amplifiers operating at MHz repetition rate.

In scientific research, most efforts to increase the average power of NIR ultrafast lasers have so far been driven by applications that require XUV pulses for various spectroscopic investigations. In parallel, other research applications areas are nowadays also emerging that benefit from the availability of ultrafast laser sources with ever-increasing average power, particularly in other regions of the electromagnetic spectrum. In general, there is a clear trend toward extending high-power operation to a wide spectral range ranging all the way from the XUV to the terahertz (THz) regime, going through the deep-UV and the mid and far-IR ranges, where laser materials are not well-established or simply do not exist for the direct generation of short pulses. This trend has been supported by the parallel progress in nonlinear conversion methods (nonlinear crystals, gas-filled hollow-core fibers, etc...), which make the use of powerful NIR lasers as pump lasers a very attractive option.

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We will focus here on this technology and aim at giving an overview of the latest state-of-the-art in order to set the stage for presenting the applications enabled by this technology. We will show that current levels of operation open up unique possibilities for their use as compact driving sources in applications where very high repetition rates (in the MHz regime) are beneficial. We will focus our attention on new applications opened up by this technology, in particular their potential to provide a path to compact MHz repetition rate THz sources for time-domain spectroscopy [2].

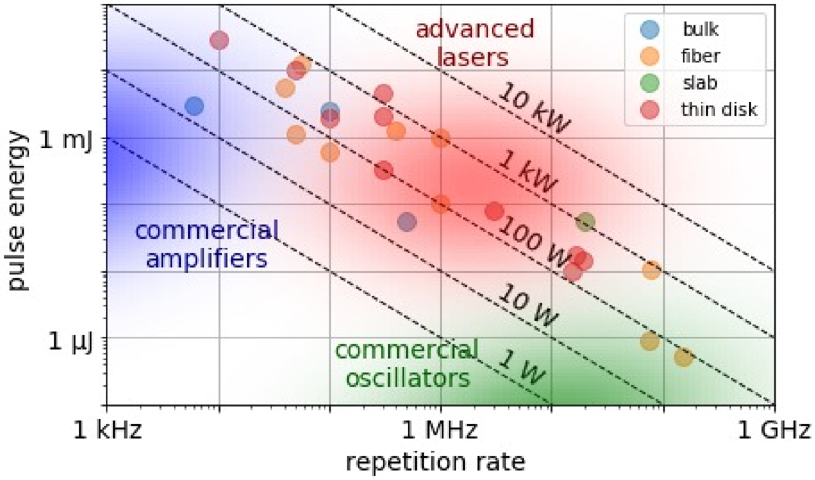

Figure 1. Overview of state-of-the-art ultrafast laser systems, based on different technologies (color code), illustrating the trend of current ultrafast laser technology towards multi-kilowatt average power.

2. MODELOCKED THIN-DISK LASERS

The thin-disk laser concept dates back to 1994 and was invented by A. Giesen and coworkers [3]. In a TDL, the gain medium is shaped like a very thin (≈100 µm) disk with a large diameter in comparison to its thickness. The back side of the disk is coated with a high reflector for both the pump and laser wavelengths, and the front side is anti-reflection coated for the same wavelengths. The back side of the disk is contacted on an appropriate heatsink (typically diamond, copper or copper-tungsten) and the gain medium can thus be efficiently water-cooled through the backside, and used in a resonator or amplifier as an “active mirror”. If the pump and laser spot sizes applied are correspondingly large (typically at least one to two orders of magnitude larger than the thickness), a one-dimensional heat-flow can be obtained, and the achievable output power can simply be scaled up by increasing the pump diameter and power by the same factor. Because of the short length of the gain medium, correspondingly small single-pass absorption and gain coefficient are typically achieved in this geometry: both efficient pumping of solid-state laser media, and efficient laser amplification in this geometry requires multiple-passes through the gain medium. For pumping, this can be achieved by pumping at an angle and placing the disk at the focus of a parabolic mirror. Multiple research groups worldwide are nowadays exploring the limits achievable with this technology. The highest average power so far achieved from an ultrafast oscillator was demonstrated in 2012: this laser system was based on an Yb:YAG SESAM-mode-locked TDL and provided 275 W, achieved with 583 fs long pulses at a repetition rate of 17 MHz [4]. The current record in terms of pulse energy followed shortly in 2014, with the demonstration of a pulse energy of 80 µJ [5], at an average power of 242 W and a pulse duration of 1.03 ps. Shortly following these demonstrations, Kerr lens mode-locked Yb:YAG TDLs also achieved comparable average power [6] and peak power levels [7], at somewhat shorter pulse durations. All record holding systems are nowadays based on Yb:YAG. Whereas many other more broadband Yb-doped materials have been mode-locked in the thin-disk geometry mostly in the goal of obtaining short pulses, most results remain in the proof-of-principle state with moderate average powers < 30 W and/or low pulse energies < 1 µJ, due to the low quality of novel gain crystals and additional difficulties related to the generation of very short pulses. In fact, only two gain materials are so far capable of achieving mode-locking at 100 W level and/or pulse energies > 10 µJ: Yb:YAG and Yb:Lu2O3 [8] . The shortest pulses demonstrated so far from a mode-locked TDL have been achieved with the gain material Yb:CALGO using Kerr-lens mode-locking, where 30 fs pulses have been reached, albeit at very low power levels. Ongoing efforts to improve the quality of this and other Yb-doped broadband gain materials are expected to bring further improvements to the achievable levels. Other promising results in this direction were achieved using Yb:Lu2O3, reaching 35 fs with 1.6 W or 10.7 W in 88 fs pulses [9].

3. TERAHERTZ GENERATION WITH HIGH-POWER THIN DISK LASERS

One unexplored area where these sources promise to open up new fields of research is for the generation of THz radiation at high average power [2]. So far, the use of mode-locked TDLs for the generation of few- or single-cycle THz ($\nu \approx 0.1 - 10$ THz) pulses via nonlinear down-conversion has not been demonstrated. Generally, sources of few or single-cycle THz pulses driven by NIR ultrafast lasers, have enabled THz time-domain spectroscopy (THz-TDS) to emerge as a powerful tool for a variety of applications, such as homeland security, non-destructive testing, imaging and drug monitoring but they also represent a powerful tool in multiple fields of research, such as material or molecular spectroscopy in chemistry and biology or for the study of condensed matter in physics. In spite of the great progress achieved in the availability of ultrafast THz sources - mostly enabled by Ti:Sapphire front ends - the lack of powerful table-top ultrafast THz sources (watt-level and beyond) remains a challenge for many applications.

Several examples of applications that are power-limited are in the biomedical field, where the strong absorption of water in the THz domain limits interesting possibilities in imaging, or even therapeutic path. More fundamentally, the study of the ultrafast molecular dynamics of liquid samples, and even more particularly aqueous samples, with THz-TDS is limited by the average power of current ultrafast THz sources. Moreover, many applications in the area of defense and security are limited because of the water vapor content of air, which makes long-range sensing a difficult task. Yet, high-power sources of THz radiation emitting short pulses are mostly restricted to accelerator-based sources. These sources currently fill the challenging frequency window of (0.1 THz –30 THz) with very high-power levels (> 10 W of (average) power can typically be achieved). However, access to these facilities remains very restrictive and costly. Furthermore, phase-stability of the generated pulses is not straightforward to achieve, making THz-TDS challenging.

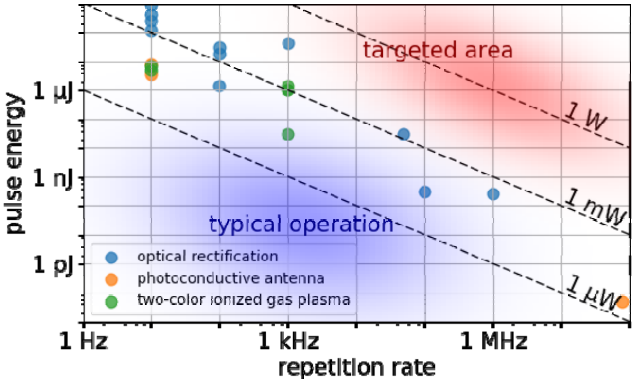

Figure 2: Overview of average power of table-top systems of few-cycle THz pulses, illustrating current power limitations.

Achieving ultrafast laser driven higher power ultrafast THz sources clearly calls for novel laser sources, capable of generating hundreds of watts to kilowatts of driving average power, regardless of the method of choice for THz generation, and mode-locked TDLs have the potential to achieve this from a compact low-noise source. In fact, conversion efficiency from the NIR to the THz rarely exceeds 1% in optimal conditions, particularly for schemes targeting the [1-10 THz] range. The most commonly used driving sources are Ti:Sa amplifiers operating at 0.8 µm, and the corresponding limitations is power are then directly mirrored in the achievable THz average power (Fig. 2). So far, most results in ultrafast laser-driven THz-sources have thus focused on achieving high pulse energy at the expense of repetition rate (thus average power). Very few existing table-top systems achieve results exceeding the mW average power level, and most commonly they operate with µW or even nW of average power. Using TDLs (both oscillators and amplifiers) as driving lasers would enable to take these sources to the watt-level. We will present our first results in this direction and show potential application areas where these sources could have impact.

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