Review

Mode-locked thin-disk lasers and their potential application for high-power terahertz generation

Clara J Saraceno

Photonics and Ultrafast Laser Science, Ruhr-Universität Bochum, Universitätsstraße 150, D-44801 Bochum, Germany

E-mail: clara.saraceno@ruhr-uni-bochum.de

Received 30 October 2017, revised 31 January 2018
Accepted for publication 20 February 2018
Published 23 March 2018

Abstract

The progress achieved in the last few decades in the performance of ultrafast laser systems with high average power has been tremendous, and continues to provide momentum to new exciting applications, both in scientific research and technology. Among the various technological advances that have shaped this progress, mode-locked thin-disk oscillators have attracted significant attention as a unique technology capable of providing ultrashort pulses with high energy (tens to hundreds of microjoules) and at very high repetition rates (in the megahertz regime) from a single table-top oscillator. This technology opens the door to compact high repetition rate ultrafast sources spanning the entire electromagnetic spectrum from the XUV to the terahertz regime, opening various new application fields. In this article, we focus on their unexplored potential as compact driving sources for high average power terahertz generation.

Keywords: high-power ultrafast lasers, mode-locked thin-disk lasers, terahertz generation, ultrafast laser applications

(Some figures may appear in colour only in the online journal)

1. Introduction

Ultrafast lasers continue to be at the forefront of many crucial scientific breakthroughs and technological achievements. The unique combination of ultrashort pulse durations and high intensities offers researchers worldwide unique possibilities to unveil the temporal dynamics of fundamental constituents of matter, as well as the potential to excite and tailor the properties of a large array of material systems. It is therefore not surprising that progress in the performance of ultrafast laser systems continuously acts as a catalyst for many new and exciting interdisciplinary fields of research.

The main workhorse of ultrafast laser science continues to be Ti:sapphire (Ti:sa) laser technology [1–3]. Commercially available Ti:sa multi-stage laser amplifiers routinely provide energetic millijoule-class pulses in the near-infrared (NIR) with durations of few tens of femtoseconds, resulting in gigawatt peak powers being readily available for a variety of experiments. As a gain material, Ti:sa offers obvious spectroscopic advantages for ultrafast laser operation [4]; it exhibits an extremely large and broadband emission cross section and good thermal conductivity, making it an excellent candidate for the...
direct generation and amplification of ultrashort pulses. However, it exhibits a relatively short gain lifetime, thus a high saturation power and high doping levels are not possible while maintaining a good crystal quality. This means that longitudinally pumped bulk crystalline media in combination with small pump spots are required to achieve efficient laser operation. The poor heat extraction in this geometry, combined with a large quantum defect, strongly limits the average power achievable from these systems to a few watts in optimum cases.

A limited average power at a given pulse energy results in an unwanted compromise in the repetition rate of the pulse train, according to $P_{av} = E_p f_{rep}$. As a result, typical Ti:sapphire amplifier systems with high energy (millijoule-level) usually operate at a repetition rate of a few kHz; on the other hand, Ti:sapphire oscillators can operate at tens of megahertz repetition rates, and up to GHz repetition rates [5], albeit with a low pulse energy of a few nanojoules and less. Therefore, researchers will often have to either operate at a low repetition rate, or simply give up research lines where high pulse energies are required.

However, Ti:sapphire laser systems remain the key enabling driver of ultrafast science. One prominent example is the field of attosecond science in strong-field physics [6] where energetic (μJ-class) and short (sub-100 fs) NIR driving pulses are most typically required for the generation of extreme ultraviolet (XUV) radiation via high harmonic generation (HHG) [7]. Most experiments making use of this XUV radiation for spectroscopic investigations thus operate with pulse trains at a few kilohertz repetition rate, limited by the availability of driving sources combining energetic pulses at a higher repetition rate. In this and many other areas of science and technology, the low repetition rate of current high-energy laser sources is a strong limitation or, in some cases, even a showstopper. Very generally, a higher repetition rate at a given (desired) high pulse energy will improve statistics in virtually any measurement method where time integrated signals are recorded, or increase measurement speed in single-shot experiments, or a beneficial combination of both.

In scientific research, most efforts to increase the average power of NIR ultrafast lasers have so far been driven by the above-mentioned applications that require XUV pulses for various spectroscopic investigations. In fact, a large number of time-resolved experimental methods using XUV pulses could be dramatically improved if higher flux was available [8]. One important example is the study of ionization processes using coincidence measurements, where long recording times are usually necessary in order to achieve reasonable statistics of the data sets [9]. In this case, a higher repetition rate allows significantly reduced measurement times and also improves signal-to-noise ratio. Another prominent example is the study of photoemission dynamics from surfaces [10], where space charge effects limit the applicable pulse intensity on the sample, therefore, a high repetition rate is desired to reach sufficient signal-to-noise ratio at lower excitation intensity. Other examples include coherent diffractive imaging [11], where higher repetition rate XUV sources allows the taking of images at higher signal-to-noise ratio thus improving spatial resolution [12], or XUV frequency comb spectroscopy [13] where a higher repetition rate means less dense combs with more power per comb line, also enabling an increase in measurement sensitivity. All these applications have already benefited enormously from the latest progress in the demonstration of table-top high average power laser systems, and continue to progress hand-in-hand as ultrafast laser sources continue to break new frontiers.

Although the focus here is placed mostly on scientific applications, it is not to be forgotten that the progress achieved in the development of more powerful ultrafast laser systems has been in a large part driven by the growing industrial market of ultrafast lasers for high-precision material processing [14]. In this case, cold ablation of a large variety of materials can be driven at higher speeds if a higher repetition rate is available at sufficiently high pulse energy. In fact, many of the most recent state-of-the-art laser systems have been demonstrated in an industrial research and development (R&D) environment [15].

In parallel to the large progress achieved in the demonstration and application of high-flux XUV sources via HHG, other research applications areas are currently 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 towards 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 makes the use of powerful NIR lasers as pump lasers a very attractive option.

In this article, the focus is placed on one specific technology that is particularly promising to provide a platform for compact and efficient high-power ultrafast sources: mode-locked thin-disk laser (TDL) oscillators. In strong contrast to most common approaches for generating high average power, which rely on multi-stage amplification, mode-locked TDLs can provide similar average powers at MHz repetition rates, from a one-box diode-pumped laser oscillator, which provides unique advantages in terms of not only compactness and reliability but also potentially pulse quality and noise. An overview of the state-of-the-art of this technology, and research directions enabled by the latest state-of-the-art will be presented in this article. We will particularly emphasize the potential of these laser sources as drivers to generate radiation in the THz regime with high average power.

2. State-of-the-art

2.1. Ultrafast laser technology at 1 μm

Recent progress in ultrafast laser technology at 1 μm wavelengths has enabled us to largely exceed the kilowatt average power level with picosecond and sub-picosecond pulses in various laser architectures [16–19] (figure 1). Commercial solutions offering hundreds of watts of average power with sub-picosecond pulses have even recently become available. This extends the application possibilities of these high-power
ultrafast sources even further, by making these systems more easily accessible.

Three laser architectures have mostly been at the origin of this extremely fast progress: thin-disk, fiber and slab lasers based on Yb-doped gain media. The main common point between these three geometries is an optimized surface-to-volume ratio of the gain medium in comparison to the bulk geometry, allowing for significantly improved heat removal and reduced thermal distortions. In addition to the geometrical advantages of each, Yb-doped materials exhibit a very small quantum defect (<10%) resulting in an intrinsically much lower heat deposition, which stands in sound contrast to Ti:sapphire. Combined with the possibility of efficient and inexpensive high-power diode pumping, Yb-doped materials have been the main driver of the immense progress achieved in energy and power scaling of ultrafast laser systems in the last decades. One drawback of laser systems based on Yb-doped materials is their typically limited gain bandwidth, which results in most state-of-the-art ultrafast systems having pulse durations close to 1 ps duration. Pulse shortening to <100 fs with state-of-the-art average power and pulse energy still requires cumbersome external and, in most cases, inefficient pulse compression schemes such as hollow-core capillaries [20], hollow-core photonic crystal fibers [21] or multi-pass cells [22, 23].

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. Sufficient gain can be achieved via multi-stage, multi-pass or regenerative amplification, depending on the corresponding gain geometry and the available seeding power. One extremely successful scheme involved multi-stage fiber-based chirped pulse amplifiers, which achieved up to 830 W of average power (640 fs–78 MHz) back in 2010 [24] from a single-channel amplifier. Further power scaling was then achieved with coherent combination techniques allowing for ultrafast fiber amplifiers to reach 1.8 kW of average power [16]. Another very successful approach for amplification of ultrashort pulses is the Innoslab architecture. Using an Yb:YAG slab, 1.1 kW of average power has already been demonstrated in 2010 [25]. Further scaling of the average power with ultrashort pulses could potentially be envisioned in this geometry, however, this has not been demonstrated so far. 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.

2.2. Ultrafast thin-disk lasers

The TDL concept dates back to 1994 and was invented by A. Giesen et al [26]. 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 back side, 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. Commercially available modules with up to 72 single-absorption passes provide the necessary platform for efficient pumping in this geometry.

Most state-of-the-art results in this geometry have been achieved with the gain material Yb:YAG [27, 28]. In fact, so far, kilowatt level powers (both in continuous wave (CW) and with ultrashort pulses) have only been achieved with this material. The reason for this is that this material offers a very attractive combination of a large emission cross section, the possibility of high doping levels without detrimental excited state absorption and quenching effects, a good thermal conductivity, a very low quantum defect, a pumping wavelength available with high-power diodes and good mechanical strength for the fabrication of high quality, large thin-disks. Last but not least, Yb:YAG benefits from many years of industrial development, and an important fraction of recent advances was realized in industrial R&D (Trumpf GmbH) [15]. In continuous-wave operation, up to 10 kW have been extracted from a single Yb:YAG disk in transverse multi-mode operation [29], and up to 4 kW in nearly single-mode operation [30]. Nevertheless, important research efforts continue to be devoted to finding other gain materials that could potentially equal and even outperform Yb:YAG [31, 32]. In particular, these efforts aim to find Yb-doped materials with broader emission bandwidth for ultrafast operation, that could also be suitable for high-power operation in this geometry [33, 34]. This effort is being carried out mostly for scientific applications, where reaching shorter pulse durations (<100 fs) at the kilowatt level, without the need for external passive pulse compression would be beneficial.
The thin-disk geometry offers a number of advantages for ultrafast operation. In particular, the large mode areas on the gain medium makes it an inherently advantageous geometry for low accumulated nonlinearities at very high pulse energies. Efficient amplification of low-power ultrafast lasers is achieved in this geometry by multiplying the number of passes through the gain medium either via regenerative or geometrical multiple passes, depending on the targeted parameters and the available seed power. Both concepts have proved extremely successful in recent years (figure 2). Thin-disk regenerative amplifiers [35, 36] have progressed particularly fast. They recently reached a record-high 200 mJ of pulse energy at 1 kW of average power in 1 ps long pulses, at 5 kHz repetition rates [18]. These systems are ideal for applications requiring very high pulse energies, at repetition rates up to \( \approx 500 \text{kHz} \). The use of multi-pass thin-disk amplifiers as booster amplifiers has progressed extremely successfully from systems capable of delivering very high pulse energy at moderate average power [37] to kW level amplifiers with large parameter flexibility [19, 38, 39]. In this case, multiple passes through the disk allow for amplification at large extraction of already powerful seed pulses, without restrictions in the repetition rate. This resulted in the demonstration of more than 2 kW of average power in ps-pulses at multi-mJ pulse energy, which to date is the record in terms of the average power of any ultrafast laser system [40].

The TDL geometry also offers the unique possibility of direct mode-locking of oscillators with very high average power. This stands in strong contrast with other geometries (fibers and slabs) and is owing to the above-mentioned small interaction volume between the pulses and the gain medium. Since their first demonstration in the year 2000 [41], 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 rates. In the following section, the focus is placed on 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. Special attention is placed 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.

2.3. Mode-locked thin-disk oscillators

2.3.1. State-of-the-art. The first demonstration of a mode-locked TDL dates back to the year 2000 in the group of Professor U Keller at ETH Zürich [41]. This first demonstration was based on an Yb:YAG TDL which was mode-locked using a semiconductor saturable absorber mirror (SESAM) [42] and achieved 16.2 W of average power and 700 fs pulses. Since then, both average power and pulse energy available from mode-locked TDLs have progressed exponentially and no fundamental show-stoppers appear for this trend to continue (figure 2). 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 [43]. The current record in terms of pulse energy followed shortly in 2014, with the demonstration of a pulse energy of 80 \( \mu \text{J} \) [44], 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 [45] and peak power levels [46], at somewhat shorter pulse durations. All record holding systems are nowadays based on Yb:YAG. Whereas many other broadband Yb-doped materials have been mode-locked in the thin-disk geometry mostly with the goal of obtaining short pulses [47–55], most results remain in the proof-of-principle state with moderate average powers <30 W and/or low pulse energies <1 \( \mu \text{J} \), due to the low quality of novel gain crystals and additional difficulties related to the generation of very short pulses. In fact, so far, only two gain materials are capable of achieving mode-locking at 100 W level and/or pulse energies >10 \( \mu \text{J} \): Yb:YAG [43–46, 56–58] and Yb:Lu2O3 [59]. 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 <1 W [60]. 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 [61].

A summary of the performance of the most recent state-of-the-art of mode-locked TDLs is given in table 1. The typical layout of a mode-locked TDL is presented in figure 3. In the near future, kilowatt level ultrafast oscillators are expected to be demonstrated, supported by improvements in various components for high-power operation.
2.3.2. Mode-locking of high-power TDLs. Historically, TDLs have most commonly been mode-locked using SESAM soliton mode-locking [62, 63]. In this mode-locking regime, the SESAM plays an important role in starting the pulses and providing, together with negative dispersion, a stabilizing mechanism against growing continuous-wave background that could potentially be amplified during the ‘long’ recovery time of the absorber, typically in the order of a few to tens of picoseconds for commonly used quantum-well absorbers. Provided that the correct balance between self-phase modulation (SPM) and negative dispersion is achieved within each round trip, soliton pulses significantly shorter than the recovery time of the ‘slow’ absorber are then generated.

The use of SESAMs is particularly well suited for mode-locking of high intracavity power TDLs, as the few-micrometer thick semiconductor structure is used in reflection (typically as an end mirror in a standing wave resonator), thus potentially also benefiting from excellent power scaling properties. The low gain per round trip inherent to TDLs, and the corresponding low gain per round trip and large intracavity pulse energy, makes the absorber properties required for stable mode-locking (moderate modulation depth, large saturation fluence, moderate recovery time) particularly well suited for designs with a high damage threshold, as well as excellent thermal properties and surface quality, which are all crucial aspects for the powers targeted. Guidelines on the design of SESAMs with tailored properties for high-power TDLs were presented in [64, 65]. Typically, high-power SESAM designs support pulse durations of a few hundreds of femtoseconds. Achieving much shorter pulse durations is also possible using SESAM mode-locking, but special SESAM design considerations need to be taken into account, making their design and fabrication for high-power levels more challenging [66, 67].

Generally, access to a broader gain bandwidth of the gain material significantly relaxes the requirements on the SESAM parameters to reach shorter pulse durations from SESAM mode-locked TDLs [62]. Therefore, an important research direction for these laser systems continues to be to find suitable broadband gain materials that could allow the extension of the state-of-the-art performance of these lasers to the sub-100 fs regime [33, 34]. As we mentioned above, current limitations in average power are mostly, but not only, due to the poor quality of the available broadband crystals.

Table 1. Performance level of state-of-the-art mode-locked thin-disk lasers, focusing on systems capable of achieving >100 W of mode-locked power.

| Year   | 2010 | 2012 | 2012 | 2014 | 2014 | 2016 |
|--------|------|------|------|------|------|------|
| Gain medium | Yb:Lu2O3 | Yb:YAG | Yb:YAG | Yb:YAG | Yb:YAG | Yb:YAG |
| Average power | 141 W | 145 W | 275 W | 270 W | 242 W | 155 W |
| Pulse energy | 2.4 µJ | 41 µJ | 17 µJ | 14.4 µJ | 80 µJ | 10 µJ |
| Pulse duration | 738 fs | 583 fs | 330 fs | 1.03 ps | 140 fs |
| Peak power | 2.8 MW | 32.2 MW | 25.6 MW | 38 MW | 66 MW | 62 MW |
| Mode-locking | SESAM | SESAM | SESAM | KLM | SESAM | KLM |

Figure 3. To-scale 3D representation of a typical high-power mode-locked thin-disk laser, in this case following the design of [43], which achieved 275 W of average power in 583 fs pulses, at a 17 MHz repetition rate. The layout of a multi-hundred-watt thin-disk laser is comparable to that of a low-power oscillator. This laser system was built in a vacuum enclosure with 1.6 m × 0.8 m. Inset: the thin-disk pumping module consists of a multi-pass arrangement where the disk is placed at the focus of a parabolic mirror. The mirrors used in the resonator are a combination of high reflectivity mirrors and negative dispersion mirrors.
This remains one of the big milestones for this laser technology and promising first steps have been achieved in this direction using Yb:Lu$_2$O$_3$ \cite{68}. Sub-100 fs oscillators with hundreds of watts of average power would be of wide interest, particularly for scientific applications where short pulses in combination with high peak powers are usually a crucial requirement (for example for HHG).

In the last few years, Kerr-lens mode-locking has also demonstrated its potential for high-power mode-locking in this laser geometry \cite{45, 46, 69}. The very fast saturable absorption provides a means to obtain shorter pulses from systems based on laser gain media with limited gain bandwidth, such as Yb:YAG. Unlike standard bulk lasers, the large laser mode areas on the thin gain disk in TDLs does not provide sufficient Kerr lensing for Kerr-lens modelocking (KLM), thus a separate intracavity element in the resonator, typically a fused silica, undoped YAG or sapphire plate is used in a focus in the resonator. The use of KLM in TDLs has largely progressed over the last few years. However, the use of this mechanism for TDL mode-locking comes at the expense of some additional design challenges: in contrast to SESAM mode-locking, self-phase modulation and self-amplitude modulation in KLM lasers are strongly coupled, thus eliminating one crucial degree of freedom which is important for lasers operating with very high intracavity average and peak power. In SESAM mode-locked TDLs, self-amplitude modulation can be tuned to a very large degree with the semiconductor structure, and self-phase modulation is negligible. In contrast, in KLM, large amounts of SPM are accumulated in the Kerr medium in order to achieve sufficient self-amplitude modulation, making the amount of negative dispersion necessary to achieve soliton mode-locking at a given intracavity peak power significantly larger than in SESAM mode-locked lasers. Whereas large amounts of negative dispersion can be introduced in the resonator with advanced dispersive mirror designs \cite{70}, it remains challenging to fabricate mirrors with good thermal properties for very high intracavity average powers \cite{71}. An additional constraint in these laser systems is the need to operate at the edge of the resonator stability to increase the sensitivity to the Kerr lensing. This makes the corresponding resonators exhibit an increased sensitivity to thermal effects in various intracavity components, such as the above-mentioned dispersive mirrors or other gain media with poorer thermal properties than Yb:YAG. So far, most KLM-TDLs were based on Yb:YAG. As mentioned previously, the first reports of KLM of other gain materials have recently been presented, albeit so far only at very moderate average power and pulse energy \cite{60, 61, 72}. However, these results represent a promising first step to reaching pulse durations approaching the few-cycle regime in a power-scalable concept, if current challenges can be overcome.

Other mode-locking mechanisms have been explored in the thin-disk geometry, however, they have so far remained in the proof-of-principle stage: most likely because the limits of soliton mode-locking have so far not been reached. One example is the chirped pulse oscillator regime for its potential to increase the pulse energy achievable: in \cite{54}, a SESAM mode-locked TDL based on Yb:KLu(WO$_4$)$_2$ in the positive dispersion regime was demonstrated for the first time, however, it achieved significantly poorer performance than the same system using soliton mode-locking. Difficulties in the fabrication of appropriate high-power SESAMs with larger modulation depths limited further exploration of this regime. The latest developments in SESAM technology for high-power oscillators \cite{64, 65, 67} could make this a potentially interesting avenue to explore. More recently, the positive dispersion regime was also explored with KLM-TDLs \cite{73}, however, in this case, this direction was not pursued further due to increasing difficulties in starting the oscillator as pulse energies were increased.

2.3.3. Ongoing challenges. The physical mechanisms of mode-locked TDLs are no different than those present in more common bulk lasers; however, several specific aspects, particularly related to the very high intracavity average and peak powers achievable, need to be taken into account in their design. These design issues were described in detail in various other reports \cite{56, 74, 75}, and here the aim is placed in summarizing the main challenges which will be crucial for the next steps.

2.3.3.1. Robust single-transverse mode operation at multi-kilowatt intracavity power. Stable mode-locking requires single-transverse mode operation, and the fundamental Gaussian mode provides the highest peak intensity and is therefore favorable for mode-locking. The thin-disk geometry is particularly well suited for achieving resonators with excellent beam quality, owing to the small thermal lensing and thermal aberrations resulting from a one-dimensional heat-flow. Therefore, it comes as no surprise that for a given power level, TDLs achieve exceptionally high brightness \cite{15}. On the other hand, simple TDL resonator designs with few passes on the gain disk inherently operate with low gain, thus they only operate efficiently at very high intracavity power. Thermal effects, damage and residual nonlinearities of intracavity components are therefore major issues in the design of these lasers. Using large laser mode areas on critical components can potentially allow us to overcome these limitations. However, as laser spot sizes are increased, resonator stability regions become increasingly sensitive to thermal effects \cite{76}. Therefore, a very precise knowledge of all thermal effects present in the resonator is necessary and can be a very challenging task. Residual thermal lensing in the gain disk can typically be compensated for with an appropriate resonator design \cite{75, 76}, when using high quality, well-established gain materials such as Yb:YAG. For other more novel gain materials, various parasitic effects such as thermally induced birefringence, anisotropic deformation or a sub-optimal heat removal due to an imperfect gluing can prevent power scaling in single-mode operation. Other intracavity components that are required for mode-locking (dispersive mirrors, polarization selection, absorber) can also exhibit thermal lensing at kilowatt intracavity power, and these can be more difficult to quantify and tackle, and can
become the main scaling limitation when intracavity powers exceed several kilowatts intracavity [43].

For future scaling of these systems to kilowatt average output powers (tens of kilowatts intracavity), resonator designs with larger spot sizes than typically used so far (cm-size versus a few mm) will be required to avoid damage and minimize parasitic nonlinearities. Minimizing thermal effects with low-loss and excellent surface quality will thus be crucial. Important efforts are currently being devoted to understanding and harnessing these detrimental effects, as well as reducing loss and improving surface quality in dispersive mirrors [71, 77] or the saturable absorber medium (SESAM or Kerr medium) [64, 65].

2.3.3.2. Stable mode-locking. In both SESAM and KLM-TDLs, soliton pulse shaping is responsible for the formation of nearly transform-limited pulses, provided that the correct balance between SPM and negative dispersion is achieved at every round trip of the pulses in the resonator [78]. However, this mechanism is only stable within a maximum tolerable nonlinear phase shift, typically between a few mrad and few hundreds of mrad. Generally, maximizing the achievable peak power from mode-locked oscillators based on soliton pulse shaping (both based on SESAM and Kerr-lens mode-locking) requires minimizing all possible sources of intracavity SPM. This is one aspect which makes TDLs unique for achieving high pulse energies, because the sources of SPM are controllable up to a large degree. In fact, it was identified early on that the propagation of the pulses in the air inside the long resonators contributed to a large degree to the total nonlinear phase shift per round trip [36, 79]; therefore, latest state-of-the-art results all operate in enclosures with low pressure helium or vacuum environments [43, 44, 46] allowing the highest pulse energies to be obtained. Another approach that has been explored with SESAM mode-locking is geometrically increasing the number of passes on the gain disk per resonator round trip to efficiently operate at lower intracavity power [80]. It is worth mentioning that this maximum tolerable nonlinear phase shift strongly depends on the absorber parameters (particularly on the modulation strength of the absorber), and thus depends on every specific resonator design and absorber type. Furthermore, although a large amount of the total nonlinearity is known and largely controllable, unknown sources of nonlinear phase shifts such as those created by mirror structures in the resonator eventually become the limiting factor in pulse energy scaling [43]. In a similar way to the above-mentioned thermal effects, a precise knowledge of these unknown nonlinearities, for example those originating from the different dispersive mirrors in the resonator, is a difficult task that is required to significantly increase the pulse energy available from these oscillators [74].

Another potential difficulty in the design of mode-locked TDLs is Q-switched mode-locking (QML) instabilities [81]. Most commonly, intracavity pulse energies are sufficiently high to overcome the QML threshold; however, in comparison to other laser technologies, TDLs operate with orders of magnitude larger mode areas on the gain medium and on the saturable absorber, particularly in laser systems with very high average power. Furthermore, Yb-doped materials most commonly used in TDLs exhibit very high saturation energies, due to the long gain lifetimes. All these factors make this an important consideration in TDLs. This is particularly important because during this regime much higher peak powers can be reached that can result in damage of various intracavity components, before stable mode-locked pulses are achieved. Increasing the overall gain by operating in a multi-pass arrangement can reduce these issues.

Last but not least, these laser systems are prone to multiple pulsing instabilities when the energy levels become excessive, such that several lower pulse energy pulses are favorable for solitary propagation in the resonator. In SESAM mode-locked TDLs, operation of the SESAM in the reflectivity rollover regime [82] accounts for multiple pulsing instabilities in most cases [83, 84] and can be avoided with SESAM designs with rollover shifted to high fluences [64] or by increasing the laser spot size on the absorber, when possible. In Kerr-lens mode-locked TDLs, few reports have been made of the onset of these instabilities but they remain a crucial issue that needs to be ruled out for every laser system.

2.3.4. Current trends. Several groups worldwide are currently exploring the performance limits achievable with this promising ultrafast technology and the current trends towards higher average and peak power appears to be only at a start. So far, most mode-locked TDLs have been demonstrated at 1 μm using Yb-doped materials and record holding systems continue to be dominated by the well-established material Yb:YAG. In the near future, it is expected that mode-locked TDLs based on Yb:YAG will continue to break new frontiers both in terms of average power and pulse energies, and approach the kilowatt and millijoule milestones.

Other Yb-doped materials with broader emission bandwidth will continue to progress in terms of quality: it is expected that the sub-100 fs regime, with hundred-watt level average power milestone will be reached in the near future. Very promising candidates in this direction are the sesquisilicate oxide material Yb:Lu2O3 and their mixed counterparts [34, 85], Yb:CALGO [86], both in the SESAM and Kerr-lens mode-locked regime. Continuing the exploration of other novel Yb-doped materials with suitable properties for the thin-disk geometry will also remain an important task in order to achieve this crucial milestone.

More recently, laser materials based on other dopant ions have started to be explored for TDL mode-locking. The first proof-of-principle demonstration of a CW Ti:sa laser in the thin-disk geometry was achieved most recently [87], reaching 7 W at 11% efficiency. Whereas the obtained value still remains moderate for the thin-disk geometry, this represents an important first milestone to potentially obtaining few-cycle mode-locked laser sources with high average power, which is challenging with Yb-doped materials. The first mode-locked Ho:YAG TDL, operating at a central wavelength of 2.1 μm based on KLM was...
also recently reported [88]. Extending the wavelength coverage available from TDLs to the mid-IR also represents an interesting research direction for this technology, which expands the application possibilities of these sources even further.

2.4. Currently explored application areas of mode-locked TDLs

The above-mentioned progress in the performance of mode-locked TDLs has triggered multiple groups to start exploring the possibilities opened by these unique laser systems as compact, low-noise driving sources for various applications that benefit from energetic pulses at a high repetition rate. Very early on, their potential as compact driving sources for strong-field physics experiments was confirmed in an experiment of photoelectron imaging spectroscopy (PEIS) at 1.03 μm using only 1 μJ pulse energy from a mode-locked TDL operating at a 14 MHz pulse repetition rate [89]. In this first experiment, it was confirmed that PEIS at multi-megahertz excitation results in a high signal-to-noise ratio, short measurement times and a high accuracy. However, their potential for this and other applications remains at a very early stage, simply because the technology is only now at its blooming stage and starts to achieve sufficiently high peak powers for most targeted applications. In fact, these days, most experiments demonstrated with mode-locked TDLs have focused on their use as pumping sources for nonlinear conversion into other more exotic spectral ranges.

2.4.1. Compact MHz XUV/VUV sources. As mentioned in the introduction, a prominent area in this field where mode-locked TDLs could potentially have a large impact is as compact driving sources for the generation of XUV/VUV radiation at high repetition rates via HHG. In many sensitive spectroscopy schemes using XUV/VUV pulses, increasing the average flux is desired rather than increasing the pulse energy at a low repetition rate. Driving HHG directly with a one-box mode-locked oscillator offers the additional benefits of simplicity compared to other amplifier driving sources and/or passive enhancement cavities, as well as the possibility to provide XUV pulses with very low noise and high contrast. The energy levels recently demonstrated from mode-locked TDLs [44] allowed achievement of HHG directly driven by a high power mode-locked TDL in 2015 [90]. Although these results represent an important first step, an external passive compression stage was required in this experiment to reach sufficiently short (in this experiment 88 fs) driving pulses. Furthermore, the performance achieved in terms of XUV flux in this experiment was moderate, and still requires improvement in order to be used for applications of the XUV pulses. These improvements are expected to be facilitated by further improvements in performance of the laser systems, which are ongoing: for example, TDLs generating significantly shorter pulses and higher pulse energy than was available at the time of this proof-of-principle experiment are expected to be demonstrated, allowing us to significantly improve these results and bring these sources to the corresponding applications. Recent progress in reducing the pulse duration directly available from thin-disk oscillators, approaching the few-cycle regime, also makes these sources an attractive option for the generation of attosecond pulses at MHz repetition rates, directly driven by a one-box table-top oscillator. Another potentially interesting avenue that allows us to overcome current output performance limitations is to make use of the intracavity enhancement of mode-locked TDLs. A first proof-of-principle experiment was recently reported [91], where HHG was demonstrated at 300 W intracavity power at 17.4 MHz repetition rate, with 267 fs long pulses using a SESAM-mode-locked Yb:Lu2O3 TDL. Although the generated XUV flux in this first experiment was also moderate, multiple improvements can also be expected when using this method: particularly by using driving pulses with higher pulse energy and shorter duration, which have already been demonstrated intracavity with this technology [50].

2.4.2. High-power stabilized frequency combs. Mode-locked high-power TDLs also provide an outstanding platform for applications where waveform synthesized pulses or stabilized frequency combs with high repetition rates are beneficial, for the dynamic excitation and control of molecular systems or for XUV precision spectroscopy. In order to make mode-locked TDLs a viable option for these applications, a sine qua non requirement is carrier-envelope phase (CEP) stabilization. In spite of this being a crucial requirement for a number of applications with large impact, the first demonstration of a carrier envelope offset (CEO) stabilized TDL was only achieved in 2013 [92]. The stabilized laser system was a SESAM-mode-locked TDL based on Yb:CALGO operating at a few watts of average power. Further investigations followed on how to extend this first demonstration to the 100 W level, but so far remains undemonstrated [93]. Full stabilization of a KLM-TDL was also demonstrated in [94], however, at a moderate average power of 27 W. The difficulty in extending these results to the >100 W level is due to several inherent challenges specific to TDLs: on the one hand, the long pulse durations >200 fs typically achieved at high-power levels are too long to directly support the generation of a coherent octave-spanning spectrum in a nonlinear fiber. This is required for standard CEO frequency detection in an f-to-2f interferometer [95], thus adding the requirement of a nonlinear compression stage to even detect the beat signal to be stabilized. Furthermore, strongly spatially multi-mode pump diodes operate at high voltage and high current in TDLs; this in combination with the limited gain lifetime of Yb-doped gain materials, makes traditional stabilization via pump modulation more challenging than in low-power ultrafast oscillators. CEP-stabilization of 100 W class mode-locked TDLs remains one crucial milestone for these laser systems. Progress in the generation of shorter pulses at high-power levels, in combination with novel CEP detection and stabilization techniques [96, 97], will provide the necessary tools to reach this goal.

2.4.3. Nonlinear conversion into the mid-IR. In parallel to the above-mentioned early efforts to demonstrate mid-IR operation
of mode-locked TDLs directly using suitable gain media, well-established 1 μm technology provides an excellent option for frequency conversion into the mid-IR using parametric nonlinear conversion. This option has started to be explored to provide energetic and/or broadband pulses in the mid-IR spectral regions where many molecular signatures are present and high-power sources enable spectroscopic measurements with higher dynamic range [98, 99].

3. Mode-locked thin-disk lasers as potential compact driving sources for high-power THz radiation

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. So far, the use of mode-locked TDLs for the generation of few- or single-cycle THz (ν ≈ 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 [100]; but they also represent a powerful tool in multiple fields of research, such as material or molecular spectroscopy in chemistry and biology [101] or for the study of superconductors in physics [102]. 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 paths [103, 104]. 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 [105]. 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 time-resolved THz-TDS studies challenging.

The most commonly used techniques for THz generation using nonlinear conversion of ultrashort pulses are presented in figure 5. 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:sapphire amplifiers operating at 0.8 μm, and the corresponding limitations in power are then directly mirrored in the achievable THz average power (figure 4). 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 taking these sources to the watt-level.

Photoconductive switches are very commonly used in THz-TDS both for emission and field resolved pulse detection. In this geometry, the frequency response and conversion efficiency that can be reached depends on input laser parameters and material properties: for a wide frequency range fast carrier rise times and good mobility are crucial parameters. For the 1 μm region, most common is the use of low-temperature-grown GaAs. Typically, laser pulses with low pulse energy (a few nanojoules) are used in this approach as strong saturation effects are observed at large pulse fluences due to the large excitation densities in the most standard structures. Furthermore, high DC-bias voltages are required and the thermal load resulting from an increased average power on the switch has represented practical challenges that have prevented significant power scaling. So far, the THz spectra are limited to the low-THz range, in particular using large-area structures. However, novel techniques have enabled researchers to partially overcome these limitations and extend the concept to higher energies: using large-area inter-digitated metal-semiconductor-metal structures the generation of high THz electric fields in the 0.2–4 THz range with up to 36 kV cm−1 was demonstrated in combination with an amplifier laser system running at 250 kHz repetition rate. Up to 1.5 mW of average power were achieved in this result for an 800 mW, 4 μJ NIR excitation, reaching an efficiency of 2 × 10⁻³ [106]. It is interesting to notice that efficient scaling of the THz emission is possible as long as the excitation power and spot size can be increased simultaneously.

Therefore, the limitation in this experiment was given by the
The active area of $1 \times 1 \text{ mm}^2$ and by the maximum laser output power of 1 W. This is a promising approach for state-of-the-art ultrafast sources with even higher average power operating at MHz repetition rates. The THz frequency spectrum span of such an emitter is limited mainly by the pulse duration of the exciting femtosecond laser, by the carrier recovery of the semiconductor and by material absorption and dispersion in the THz range. This limits the available bandwidth of typical semiconductor switches to frequencies $< 3 \text{ THz}$, which is sufficient for many applications.

The most popular technique to reach high pulse energy is the use of optical rectification (OR) in $\chi^{(2)}$ nonlinear crystals. The nature of the emission, in particular the frequency range covered and the conversion efficiency achievable, are strongly dependent on the nonlinear material chosen for the generation and the parameters of the excitation pulses. The main constraints in the choice of a nonlinear crystal for a given pumping wavelength and desired THz frequency are mainly imposed by velocity-matching considerations. Large nonlinear optical susceptibilities are of course desired, but in order to efficiently convert pump photons by OR, matching of the phase velocity of the THz pulse to the group velocity of the optical-pump pulse needs to be achieved. Moreover, the maximum crystal length is restricted by dispersion in the THz regime. Collinear OR in room-temperature phase-matched semiconductor materials such as GaAs, GaP or ZnTe is most commonly used, due to the simplicity of implementation. At a typical excitation wavelength of 0.8 $\mu$m these materials are strongly limited in pulse energy by two-photon absorption (TPA). So far, the maximum pulse energy achieved is 1.5 $\mu$J, obtained with ZnTe at very low efficiency ($3 \times 10^{-5}$) using typical Ti:sapphire 0.8 $\mu$m pumping [107]. The use of OR in GaP could be a potentially viable path for mode-locked Yb:YAG TDLs, provided that thermal effects and damage thresholds can be harnessed. Few reports have been made of the thermal effects and damage properties of materials of OR [108], and these investigations will need to be extended to the operation regime of TDLs. Another promising family of materials for OR are organic crystals such as DAST or DSTMS, which achieve record-high efficiencies exceeding 3% have been reported [114]. This makes it a good candidate for high-average driving powers, particularly as LiNbO$_3$ is a well-established nonlinear material, and large crystals are available. Furthermore, it has been shown that pulse durations of approximately 500 fs are optimal for high conversion efficiency in this scheme [115], which is perfectly suited for mode-locked TDLs. In [116], a proof-of-principle demonstration at 1 MHz repetition rate using a 14 W–1 MHz fiber amplifier source operating at 1.035 $\mu$m was reported, achieving 0.25 mW average power. In this experiment, no heating due to the high average power pumping was observed. One recent result reported THz generation in LiNbO$_3$ using a thin-disk regenerative amplifier as a driving laser, but only using 6 W of driving power [117]. More recently, a chirped pulse thin-disk amplifier was used at 1 kHz to drive the generation of intense THz pulses using the same method, however, this was also at a moderate average power of 10 W [118]. Excitation with the high-average power available from TDLs (hundreds of watts) and moderately high pulse energy (tens of $\mu$J) has so far not been thoroughly explored, and represents a significantly more challenging regime of operation.

Many applications require tunable pulses in the THz domain: difference-frequency generation (DFG) of two pulses is in this case more appropriate than OR. The concept is very similar to that of OR, only the mixing process occurs between two pulses which are frequency shifted. Remarkable results have been achieved using this technique [119] by mixing the output of two twin optical parametric amplifiers (OPAs) sharing the same white light seed. THz transients with $>100 \text{ MV cm}^{-1}$ with pulse energies up to 19 $\mu$J and average powers of 19 mW were achieved using this scheme, which could potentially be extended to higher repetition rates and higher power by using TDLs as pumping sources for OPA.

THz generation via two-color filamentation [120] is very well suited for applications requiring broadband THz radiation, which can cover the whole THz spectrum and beyond. In this case, no crystal phonon resonances are present, thus extremely broadband radiation can be achieved, limited by the excitation pulse duration. Another important advantage of this technique is that there is no damage limitation, thus extremely high energies and average powers can be used. Last but not least, as no crystal phonon resonances distort the achievable spectrum, this technique yields the highest field strength for a given pulse energy. Using this technique, a very promising result yielded fields exceeding $8 \text{ MV cm}^{-1}$ with pulse energies of only 1 $\mu$J demonstrated in the 0.1–10 THz region at a 1 kHz repetition rate [121]. The main drawback of this technique is the very low efficiency achieved (typically $10^{-4} \text{–} 10^{-5}$) and the high pulse energy required (several hundreds of $\mu$J to millijoules). Recently, mode-locked TDLs have been shown to be already capable of reaching sufficient intensity for HHG in a gas target, therefore, this is an interesting avenue to explore as a potential path for broadband THz sources with MHz repetition rates. This option will become particularly attractive as the pulse duration of energetic TDLs progresses to shorter durations, since the obtainable bandwidth is directly related to the pulse width.
4. Conclusion and outlook

Mode-locked TDLs are an attractive compact and powerful ultrafast laser source for a variety of applications requiring high repetition rates in the MHz regime. State-of-the-art systems achieve several hundreds of watts of average power (up to 275 W) and several tens of μJ (up to 80 μJ) from a one-box multi-MHz oscillator, which is comparable to what can be achieved with multi-stage amplifier systems operating at these high repetition rates. These systems provide a unique platform for high-power sources spanning a wide range of the electromagnetic spectrum from the XUV to the THz. Current directions of research are extending these limits to the kilowatt level and millijoule pulse energy, finding potential ways to extend this record performance with much shorter pulse durations <100 fs as well as extending the spectral coverage of modelocked TDLs into the mid-IR.

The application potential of these sources is only now starting to bloom. Several unexplored areas could benefit from the latest state-of-the-art of these compact ultrafast sources. In particular, the generation of energetic THz pulses at high average power is an unexplored avenue that could open up several fields of research, in areas as diverse as physics, chemistry, biology, medicine or engineering.

Acknowledgments

C J Saraceno acknowledges support by the Sofja Kovalevskaja Award of the Alexander von Humboldt Foundation, and the German Cluster of Excellence RESOLV (EXC 1069).

ORCID iDs

Clara J Saraceno https://orcid.org/0000-0002-7369-9057

References

[1] Spence D E, Kean P N and Sibbett W 1990 Sub-100 fs pulse generation from a self-modelocked Ti:sapphire laser Conf. Lasers and Electro-Optics (CLEO) (Anaheim, CA) p CPDP10
[2] Spence D E, Evans J M, Sleat W E and Sibbett W 1991 Regenerately initiated self-modelocked Ti:sapphire laser Opt. Lett. 16 1762–4
[3] Sibbett W, Lagatsky A A and Brown C T A 2012 The development and application of femtosecond laser systems Opt. Express 20 6989–7001
[4] Moulton P F 1986 Spectroscopic and laser characteristics of Ti:Al2O3 J. Opt. Soc. Am. B 3 125–32
[5] Bartels A, Heinecke D and Diddams S A 2008 Passively mode-locked 10 GHz femtosecond Ti:sapphire laser Opt. Lett. 33 1905–7
[6] Calegari F, Sansone G, Stagira S, Vozzi C and Nisoli M 2016 Advances in attosecond science J. Phys. B: At. Mol. Opt. Phys. 49 062001
[7] Ferray M, L’Huillier A, Li X F, Lompré L A, Mainfray G and Marcus C 1988 Multiple-harmonic conversion of 1064 nm radiation in rare gases J. Phys. B: At. Mol. Opt. Phys. 21 L31–5
[8] Leone S R et al 2014 What will it take to observe processes in ‘real time’? Nat. Photon. 8 162–6
[9] Ulrich J, Dörner R, Mergel V, Jagutzki O, Spielerber L and Schmidt-Böcking H 1994 Cold-target recoil-ion momentum spectroscopy: first results and future perspectives of a novel high-resolution technique for the investigation of collision induced many- particle reactions Comments At. Mol. Phys. 30 285–304
[10] Zhang C H and Thumm U 2009 Attosecond photoelectron spectroscopy of metal surfaces Phys. Rev. Lett. 102 123601
[11] Miao J W, Ishikawa T, Robinson I K and Murnane M M 2015 Beyond crystallography: diffractive imaging using coherent x-ray light sources Science 348 530–5
[12] Tadesse G K et al 2016 High speed and high resolution tabletop nanoscale imaging Opt. Lett. 41 5170–3
[13] Cingoz A et al 2012 Direct frequency comb spectroscopy in the extreme ultraviolet Nature 482 68–71
[14] Malinauskas M et al 2016 Ultrafast laser processing of materials: from science to industry Light Sci. Appl. 5 e16133
[15] Schad S-S, Stolzenburg C, Michel K and Sutter D 2014 Latest advances in high brightness disk lasers Laser Tech. J. 11 49–53
[16] Müller M et al 2017 16 channel coherently-combined ultrafast fiber laser Laser Congress 2017 (ASSL, LAC)
[17] Russbuehl P, Mans T, Weitenberg J, Hoffmann H D and Poprawe R 2010 Compact diode-pumped 1.1 kW Yb:YAG Innoslab femtosecond amplifier Opt. Lett. 34 4169–71
[18] Nubbemeyer T et al 2017 1 kW, 200 mJ picosecond thin-disk laser system Opt. Lett. 42 1381–4
[19] Negel J P et al 2015 Ultrafast thin-disk multipass laser amplifier delivering 1.4 kW (4.7 mJ, 1030 nm) average power converted to 820 W at 515 nm and 234 W at 343 nm Opt. Express 23 71064–77
[20] Hadrich S et al 2013 Nonlinear compression to sub-30 fs, 0.5 mJ pulses at 135 W of average power Opt. Lett. 38 3866–9
[21] Emaury F et al 2014 Efficient spectral broadening in the 100 W average power regime using gas-filled kagome HC-PCF and pulse compression Opt. Lett. 39 6843–6
[22] Weitenberg J et al 2017 Multi-pass-cell-based nonlinear pulse compression to 115 fs at 7.5 μJ pulse energy and 300 W average power Opt. Express 25 20502–10
[23] Schulte J, Sartorius T, Weitenberg J, Vernaleken A and Russbeuldt P 2016 Nonlinear pulse compression in a multi-pass cell Opt. Lett. 41 4511–4
[24] Eidam T et al 2010 Femtosecond fiber CPA system emitting 830 W average output power Opt. Lett. 35 94–6
[25] Russbeuldt P, Mans T, Weitenberg J, Hoffmann H D and Poprawe R 2010 Compact diode-pumped 1.1 kW Yb:YAG INNOSLAB femtosecond amplifier Opt. Lett. 35 4169–71
[26] Giesen A, Hügel H, Voss A, Wittig K, Brauch U and Opower H 1994 Scalable concept for diode-pumped high-power solid-state lasers Appl. Phys. B 58 365–72
[27] Lacovara P, Choi H K, Wang C A, Aggarwal R L and Fan T Y 1991 Room-temperature diode-pumped Yb:YAG laser Opt. Lett. 16 1089–91
[28] Fan T Y 1993 Heat generation in Nd:YAG and Yb:YAG IEEE J. Quantum Elect. 29 1457–9
[29] Gottwald T et al 2012 Recent disk laser development at Trumpf SPIE Security + Defence p 8
[30] Gottwald T, Kuhn, V, Schad S, Stolzenburg C and Killi A 2013 Recent developments in high power thin disk lasers at TRUMPF laser Proc. SPIE 8989 89890P
[31] H. Feil K et al 2010 Thermal and laser properties of Yb:LuAG for kW thin disk lasers Opt. Express 18 20712–22
[32] Diebold A et al 2017 High-power Yb:GGG thin-disk laser oscillator: first demonstration and power-scaling prospects Opt. Express 25 14528–62
[33] Südmeyer T et al 2009 High-power ultrafast thin disk laser oscillators and their potential for sub-100-femtosecond pulse generation Appl. Phys. B 97 281–95
[34] Beil K et al 2013 Yb-doped mixed sesquioxides for ultrashort pulse generation in the thin disk laser setup Appl. Phys. B 113 13–8
[35] Höning C, Johannsen I, Moser M, Zhang G, Giesen A and Keller U 1997 Diode-pumped thin disk Yb:YAG regenerative amplifier Appl. Phys. B 65 423–6
[36] Metzger T et al 2009 High-repetition-rate picosecond pump laser based on a Yb:YAG disk amplifier for optical parametric amplification Opt. Lett. 34 2123–5
[37] Antognini A et al 2009 Thin-disk Yb:YAG oscillator–amplifier laser, ASE, and effective Yb:YAG lifetime IEEE J. Quantum Electron. 45 983–95
[38] Negel J P et al 2013 1.1 kW average output power from a thin-disk multipass amplifier for ultrafast laser pulses Opt. Lett. 38 5442–5
[39] Negel J P et al 2017 Thin-disk multipass amplifier for fs pulses delivering 400 W of average and 2.0 GW of peak power for linear polarization as well as 235 W and 1.2 GW for radial polarization Appl. Phys. B 123 156
[40] Negel J, Loescher A, Bauer D, Sutter D, Killi A, Abdou A and Graf T 2016 Second generation thin-disk multipass amplifier delivering picosecond pulses with 2 kW of average output power Lasers Congress 2016 (ASLL, LSC, LAC) OSA Technical Digest (Optical Society of America) ATu4.A.5
[41] Aus der Au J et al 2000 16.2 W average power from a diode-pumped femtosecond Yb:YAG thin disk laser Opt. Lett. 25 859–61
[42] Keller U et al 1996 Semiconductor saturable absorber mirrors (SESAMs) for femtosecond to nanosecond pulse generation in solid-state lasers IEEE J. Sel. Top. Quantum Electron. 2 435–53
[43] Saraceno C J et al 2012 275 W average output power from a femtosecond thin disk oscillator operated in a vacuum environment Opt. Express 20 23535–41
[44] Saraceno C J et al 2014 Ultrafast thin-disk laser with 80 μJ pulse energy and 242 W of average power Opt. Lett. 39 9–12
[45] Brons J et al 2014 Energy scaling of Kerr-lens mode-locked thin-disk oscillators Opt. Lett. 39 6442–5
[46] Brons J, Pervak V, Bauer D, Sutter D, Pronin O and Krausz F 2016 Powerful 100 fs-scale Kerr-lens mode-locked thin-disk oscillator Opt. Lett. 41 3567–70
[47] Saraceno C J et al 2011 SESAMs for high-power femtosecond mode-locking: power scaling of an Yb:Lu2ScO3 thin disk laser to 23 W and 235 fs Opt. Express 19 20288–300
[48] Saraceno C J et al 2011 First CW and mode-locked operation of an Yb:(Sc, Y), Lu2O3 thin-disk laser CLEO 2011 Laser Applications to Photonic Applications OSA Technical Digest (Optical Society of America) CWPI
[49] Dannenbecker B, Ahmed M A and Graf T 2016 SESAM-mode locked Yb:CaF2 thin-disk-laser generating 285 fs pulses with 1.78 μJ of pulse energy Laser Phys. Lett. 13 055801
[50] Diebold A et al 2013 62 fs pulses from a SESAM mode-locked Yb:CALGO thin disk laser Opt. Lett. 38 3842–5
[51] Wentks S K, Zheng L H, Xu J, Ahmed M A and Graf T 2012 Passively mode-locked Yb3+:Sc2SiO5 thin-disk laser-optic disk Opt. Lett. 37 4750–2
[52] Heckel O H et al 2010 Continuous-wave and mode-locked Yb: YCOB thin disk laser: first demonstration and future prospects Opt. Express 18 19201–8
[53] Brunner F et al 2002 240 fs pulses with 22 W average power from a mode-locked thin-disk Yb:KY(WO4)2 laser Opt. Lett. 27 116–22
[54] Palmer G, Schultzze M, Siegel M, Emons M, Bünting U and Morgen U 2008 Passively mode-locked Yb:KLu(WO4)2 thin-disk oscillator operated in the positive and negative dispersion regime Opt. Lett. 33 1608–10
[55] Tokurakawa M et al 2012 Continuous wave and mode-locked Yb3+:Y2O3 ceramic thin disk laser Opt. Express 20 10847–53
[56] Marchese S V et al 2008 Femtosecond thin disk laser oscillator with pulse energy beyond the 10-microjoule level Opt. Express 16 6397–407
[57] Neuhauß J et al 2008 Subpicosecond thin-disk laser oscillator with pulse energies of up to 25.9 microjoules by use of an active multipass geometry Opt. Express 16 20530–9
[58] Bauer D, Zawischa I, Sutter D H, Killi A and Dekorsy T 2012 Mode-locked Yb:YAG thin-disk oscillator with 41 μJ pulse energy at 145 W average infrared power and high power frequency conversion Opt. Express 20 9698–704
[59] Baer C R E et al 2010 Femtosecond thin disk laser with 141 W of average power Opt. Lett. 35 2302–4
[60] Modsching N, Paradis C, Labuye F, Gaponenko M, Graumann I J, Diebold A, Emaury F, Wittwer V J, Südmeyer T et al 2018 Kerr lens mode-locked Yb:CALGO thin-disk laser Opt. Lett. 43 879–82
[61] Paradis C, Modisching N, Wittwer V J, Deppe B, Kranckel C and Südmeyer T 2017 Generation of 35 fs pulses from a Kerr lens mode-locked Yb:Lu2O3 thin-disk laser Opt. Express 25 14918–25
[62] Paschotta R and Keller U 2001 Passive mode locking with low saturable absorbers Appl. Phys. B 73 653–62
[63] Kärtner F X and Keller U 1995 Stabilization of soliton-like pulses with a slow saturable absorber Opt. Lett. 20 16–8
[64] Saraceno C J et al 2012 SESAMs for high-power oscillators: design guidelines and damage thresholds IEEE J. Sel. Top. Quantum Electron. 18 29–41
[65] Diebold A et al 2016 Optimized SESAMs for kilowatt-level ultrafast lasers Opt. Express 24 10512–26
[66] Saraceno C J et al 2013 Cutting-edge high-power ultrafast thin disk oscillators Appl. Sci. 3 355–95
[67] Alfieri C G E, Diebold A, Emaury F, Gini E, Saraceno C J and Keller U 2016 Improved SESAMs for femtosecond pulse generation approaching the kW average power regime Opt. Express 24 27587–99
[68] Graumann I J et al 2017 Peak-power scaling of femtosecond Yb: Lu2O3 thin-disk lasers Opt. Express 25 22519–36
[69] Pronin O et al 2011 High-power 200 fs Kerr-lens mode-locked Yb:YAG thin-disk oscillator Opt. Lett. 36 4746–8

[70] Fedulova E et al 2015 Highly-dissipative mirrors reach new levels of dispersion Opt. Express 23 13788–93

[71] Angelov I B, von Pechmann M, Trubetskov M K, Krausz F and Pervak V 2013 Optical breakdown of multilayer thin-films induced by ultrashort pulses at MHz repetition rates Opt. Express 21 31453–61

[72] Kreipe B, de Andrade J R C, Krankel C and Morgner U 2016 Kerr-lens mode-locked Yb:Lu2O3 thin-disk laser 2016 Conf. Lasers and Electro-Optics (CLEO)

[73] Pronin O et al 2012 High-power Kerr-lens mode-locked Yb:YAG thin-disk oscillator in the positive dispersion regime Opt. Lett. 37 3543–5

[74] Saraceno C J et al 2015 Toward millijoule-level high-power ultrafast thin-disk oscillators IEEE J. Sel. Top. Quantum Electron. 21 106–23

[75] Baer C R E et al 2012 Frontiers in passively mode-locked high-power thin disk laser oscillators Opt. Express 20 7054–65

[76] Magni V 1987 Multielement stable resonators containing a variable lens J. Opt. Soc. Am. A 4 1962–9

[77] Razskazovskaya O, Luu T T, Trubetskov M, Goulielmakis E and Pervak V 2015 Nonlinear absorbance in dielectric multilayers Optica 2 803–11

[78] Mollenauer L F and Stolen R H 1984 The soliton laser Opt. Lett. 19 13–5

[79] Marchese S V, Südmeyer T, Golling M, Krausz F and Pervak V 2015 Nonlinear optical instability inside a mode-locked thin-disk laser oscillator Opt. Lett. 42 5170–3

[80] Klenner A et al 2013 Phase-stabilization of the carrier-envelope-offset frequency of a SESAM mode-locked thin disk laser Opt. Express 21 24770–80

[81] Emaury F et al 2015 Frequency comb offset dynamics of SESAM mode-locked thin disk lasers Opt. Express 23 21836–56

[82] Pronin O et al 2015 High-power multi-megahertz source of waveform-stabilized few-cycle light Nat. Commun. 6 6988

[83] Telle H R, Steinmeyer G, Dunlop A E, Stenger J, Sutter D H and Keller U 1999 Carrier-envelope offset phase control: a novel concept for absolute optical frequency measurement and ultrashort pulse generation Appl. Phys. B 69 327–32

[84] Seidel M et al 2016 Carrier-envelope-phase stabilization via dual wavelength pumping Opt. Lett. 41 1853–6

[85] Hoffmann M, Schilt S and Sudmeyer T 2013 CEO stabilization of a femtosecond laser using a SESAM as fast opto-optical modulator Opt. Express 21 30054–64

[86] Pupeza I et al 2015 High-power sub-two-cycle mid-infrared pulses at 100 MHz repetition rate Nat. Photon. 9 721

[87] Petersen T, Zuegel J D and Bronagle J 2017 High-average-power, 2-µm femtosecond optical parametric oscillator synchronously pumped by a thin-disk, mode-locked laser Opt. Express 25 8840–4

[88] Liu H B, Zhong H, Karpowicz N, Chen Y Q and Zhang X C 2007 Terahertz spectroscopy and imaging for defense and security applications Proc. IEEE 95 1514–27

[89] Ajiro K and Uno Y 2011 THz chemical imaging for biological applications IEEE Trans. Terahertz Sci. Technol. 1 293–300

[90] Nuss M C, Goosen K W, Gordon J P, Mankiewich P M, Omalley M L and Bhushan M 1991 Terahertz time-domain measurement of the conductivity and superconducting band-gap in niobium J. Appl. Phys. 70 2229–35

[91] Weightman P 2012 Prospects for the study of biological systems with high power sources of terahertz radiation Phys. Biol. 9 053001

[92] Yu C, Fan S, Sun Y and Pickwell-Macpherson E 2012 The potential of terahertz imaging for cancer diagnosis: a review of investigations to date Quant. Imaging Med. Surg. 2 33–45

[93] Green B et al 2016 High-field high-repetition-rate sources for the coherent THz control of matter Sci. Rep. 6 22256

[94] Beck M et al 2010 Impulsive terahertz radiation with high electric fields from an amplifier-driven large-area photodetector antenna Opt. Express 18 9251–7

[95] Blanchard F et al 2007 Generation of 1.5 μJ single-cycle terahertz pulses by optical rectification from a large aperture ZnTe crystal Opt. Express 15 13212–20

[96] Li Y et al 2011 Experimental study on GaP surface damage threshold induced by a high repetition rate femtosecond laser Appl. Opt. 50 15985–62

[97] Vicario C, Ovchinnikov A V, Ashitkov S I, Agranat M B, Fortov V E and Hauri C P 2016 Generation of 0.9 mJ THz radiation with high electric fields from BNA organic crystal pumped at Ti:sapphire frequency doubling J. Appl. Phys. 119 043510

[98] Stolen R H, Herzog W P, Brabec R A and Hauri C P 2016 Intense THz source based on BNA organic crystal pumped at Ti:sapphire wavelength Opt. Lett. 41 1777–80

[99] Monoszlai B, Vicario C, Jazbinsek M and Hauri C P 2013 High-energy terahertz pulses from organic crystals: DAST
and DSTMS pumped at Ti:sapphire wavelength Opt. Lett. 38 5106–9

[112] Hebling J, Almasi G, Kozma I Z and Kuhl J 2002 Velocity matching by pulse front tilting for large-area THz-pulse generation Opt. Express 10 1161–6

[113] Fulop J A et al 2014 Efficient generation of THz pulses with 0.4 mJ energy Opt. Express 22 20155–63

[114] Huang S W, Granados E, Huang W R, Hong K H, Zapata L E and Kartner F X 2013 High conversion efficiency, high energy terahertz pulses by optical rectification in cryogenically cooled lithium niobate Opt. Lett. 38 796–8

[115] Fulop J A, Palfalvi L, Almasi G and Hebling J 2011 Design of high-energy terahertz sources based on optical rectification Opt. Express 19 22950–22950

[116] Hoffmann M C et al 2008 Fiber laser pumped high average power single-cycle terahertz pulse source Appl. Phys. Lett. 93 141107

[117] Schneider W et al 2014 800 fs, 330 µm J pulses from a 100 W regenerative Yb:YAG thin-disk amplifier at 300 kHz and THz generation in LiNbO3 Opt. Lett. 39 6604–7

[118] Ochi Y et al 2015 Yb:YAG thin-disk chirped pulse amplification laser system for intense terahertz pulse generation Opt. Express 23 15057–64

[119] Sell A, Leitenstorfer A and Huber R 2008 Phase-locked generation and field-resolved detection of widely tunable terahertz pulses with amplitudes exceeding 100 MV cm−1 Opt. Lett. 33 2767–9

[120] Cook D J and Hochstrasser R M 2000 Intense terahertz pulses by four-wave rectification in air Opt. Lett. 25 1210–2

[121] Oh T I, Yoo Y J, You Y S and Kim K Y 2014 Generation of strong terahertz fields exceeding 8 MV cm−1 at 1 kHz and real-time beam profiling Appl. Phys. Lett. 105 041103