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Kerr-Lens Mode-Locked High-Power Thin-Disk Oscillators

Oleg Pronin and Jonathan Brons

Abstract

Femtosecond Kerr-lens mode-locked thin-disk oscillators constitute a peak- and average power scalable oscillator concept. Over last several years, they were developed directly to provide unprecedentedly high average and peak power levels of more than 200 W and more than 50 MW, respectively—the parameter range of more complex amplification systems. These developments were accompanied by many challenges, including the initiation of mode-locking, thermal lensing and the oscillator stability. These challenges were successfully overcome, resulting in a better understanding of power scaling of this technology. We offer an overview over these diverse aspects and show that this technology has a very bright future not only for further power scaling but also in terms of applications. In particular, this type of oscillator can enable a novel class of compact, table-top powerful extreme-ultraviolet and infrared radiation sources paving the way towards new spectroscopic applications.

Keywords: solid state lasers, femtosecond, thin disk, power scaling, diode pumped

1. Introduction

Femtosecond lasers can be classified in terms of output parameters such as pulse duration, repetition rate, average power, peak power, carrier envelope phase stability (CEP), intensity noise and long-term stability. Depending on the application, only a few parameters out of that list can be interesting. The choice of a certain laser or oscillator technology is usually driven by applications and, ultimately, the users and the market will define which technology is beneficial for which application. However, before a certain technology is commercially pursued, researches invest many efforts in demonstrating its potential for diverse applications. This is currently happening to the thin-disk (TD) oscillators. Meanwhile, technologies like femtosecond slab

amplifiers [1] and fiber amplifiers [2] operating in the MHz repetition rate range have become commercially available and are already on the way to facilitating real applications. Compared to amplifiers, thin-disk oscillators are more compact and simple alternatives with some characteristics, which can be superior to amplifiers.

Originally, the authors' motivation was to pursue research applications in two far separated spectral ranges: extreme ultraviolet (XUV) and middle infrared radiation (MIR). Ideally, the laser sources described here would provide access to both broadband radiation in the XUV, the deep UV range 13–200 nm and broadband radiation in the infrared range 3–30 μm. Due to the intrinsic simplicity and compactness of thin-disk oscillators, these sources would serve as table-top alternatives to synchrotron beamlines [11, 12]. Moreover, this broadband radiation can be turned into frequency combs [13, 14] with some additional stabilization efforts [5] or even into a table-top attosecond pulse source [15, 16]. Consequently, direct frequency comb or dual frequency comb spectroscopy in the XUV and MIR regions would be advanced significantly with respect to the current state of the art. In addition, these sources can be transportable and would thus benefit more experiments and collaborations in the research community.

Rapid progress in the development of Yb-doped lasers was mainly supported by the availability of inexpensive pump sources, namely InGaAs diodes [17]. The price of these pump diodes has kept on decreasing over the last years due to increasing demand in industrial applications. Considering the current price of pump laser diodes, even moderate optical to optical efficiencies of femtosecond oscillators are not of a serious concern, especially for applications in research. The invention of Kerr-lens mode-locking [18] in combination with Ti:Sapphire (Ti: SA) [19] as gain-material had profound impact on applications both within and outside of research. When taking a closer look into the progress made in Ti:Sa and Yb:YAG, thin-disk oscillators one can conclude that the Yb-based TD oscillators resemble the technological evolution of the Ti:Sa oscillators. The main advantage of Yb-based TD technology is its peak and average power scalability with the access to relatively cheap pump diode sources. However, the Ti:Sa gain medium is uniquely broadband and delivers light in the visible range being hardly accessible to Yb-based gain media. Thus, Yb-based TD technology cannot completely substitute the Ti:Sa technology, especially in applications where no high average powers are required. Moreover, as soon as direct diode pumping of Ti:Sa oscillators will settle as the routine pumping scheme, a next competition round is to be expected between Yb-based and solid-state Ti:Sa oscillators, especially in the low average power regime. For those applications requiring XUV and MIR radiation, the intrinsic scalability of the thin-disk concept is of crucial importance. For instance, conversion efficiencies from a 1 μm driving source into the XUV hardly exceed 10^{-5} [20] and 10^{-3} into the MIR, when simple intra-pulse difference frequency generation is considered [21]. Thus, reasonable average powers in the mW-W range which are necessary for spectroscopy applications can be obtained by using very high average powers of the driving laser, on the order of 100–1000 W. It should be mentioned that femtosecond enhancement cavities [22–24] represent another type of technology well suitable for XUV generation experiments. So far, only by means of this relatively complex technology, direct XUV frequency comb spectroscopy was demonstrated [25] and highest average powers were achieved.

We consider femtosecond oscillators delivering average powers >100 W, pulse durations on the order of 200 fs and repetition rates of a few tens of MHz (see summary **Table 1** on various oscillators). These parameters are obtained directly from oscillators without the involvement of any type of external amplification. From this perspective, thin-disk oscillators represent a separate class of lasers uniquely combining high peak and high average powers. Their main features are the amplification free nature, low noise and relative compactness. Further-on in the text, we focus only on this type of technology and omit any type of amplifiers or enhancement cavities.

The first mode-locked Yb:YAG thin-disk oscillator was demonstrated in the group of Prof. Keller [27] in 2000. That paper essentially merged two available technologies: the thin-disk and Semiconductor Saturable Absorber Mirrors (SESAM). The same group advanced this technology during the next decade and established many records in terms of peak power, pulse energy [28] and average power [29] directly obtained from femtosecond oscillators. Also other groups pushed these limits [30, 31] and investigated different gain materials and dispersion regimes [32]. However, the obvious merge of the Kerr-lens mode-locking (KLM) technique with the TD technology was not demonstrated till 2012 [33]. Although the basic idea of merging these two technologies was patented in 1999 [34], the experimental attempts to realize it were unsuccessful according to [35]. In 2012, the merging of KLM and TD technology was successfully demonstrated in our group [33]. This first encouraging experiment motivated us to proceed further in this direction. Over the last 5 years, numerous TD KLM oscillators were developed with other groups also joining this activity [36–38]. The oscillators developed in our group are summarized in **Table 1** and are also shown as red dots in **Figure 1**. Additionally, the rapid evolution of TD KLM oscillators is shown in **Figure 2b**.

P_{avg}, W	E_p, µJ	f_{rep}, MHz	τ_p, fs	P, MW	P_{avg}, W (compressed)	τ_p, fs (compressed)	Application	Status
40	3	13	300	9			Seed oscillator	In use [3]
90	0.9	100	250	3.5	>50	20	MIR generation	In use [4]
42	1.1	38	250	4.2	6 (10)	7.7 (10)	MIR generation	In use [5, 6]
270	14	19	330	37.8			Development itself	Not in use [7]
155	10	15.5	140	63	130	30	XUV generation, Raman spectroscopy	In use [8]
10 (3.5)	0.7 (0.4)	100–200	70 (47)	0.6			Development itself	In use [9]
100	4.1	24	190	19.3	65	30	Commercial system	In use [10]

All oscillators use Yb:YAG as a gain medium. Most of the oscillators are successfully operating in the laboratories with the parameter sets originally published.

Table 1. Summary table of the KLM thin-disk oscillators developed at MPQ, LMU and UFI GmbH from 2012 till 2017.
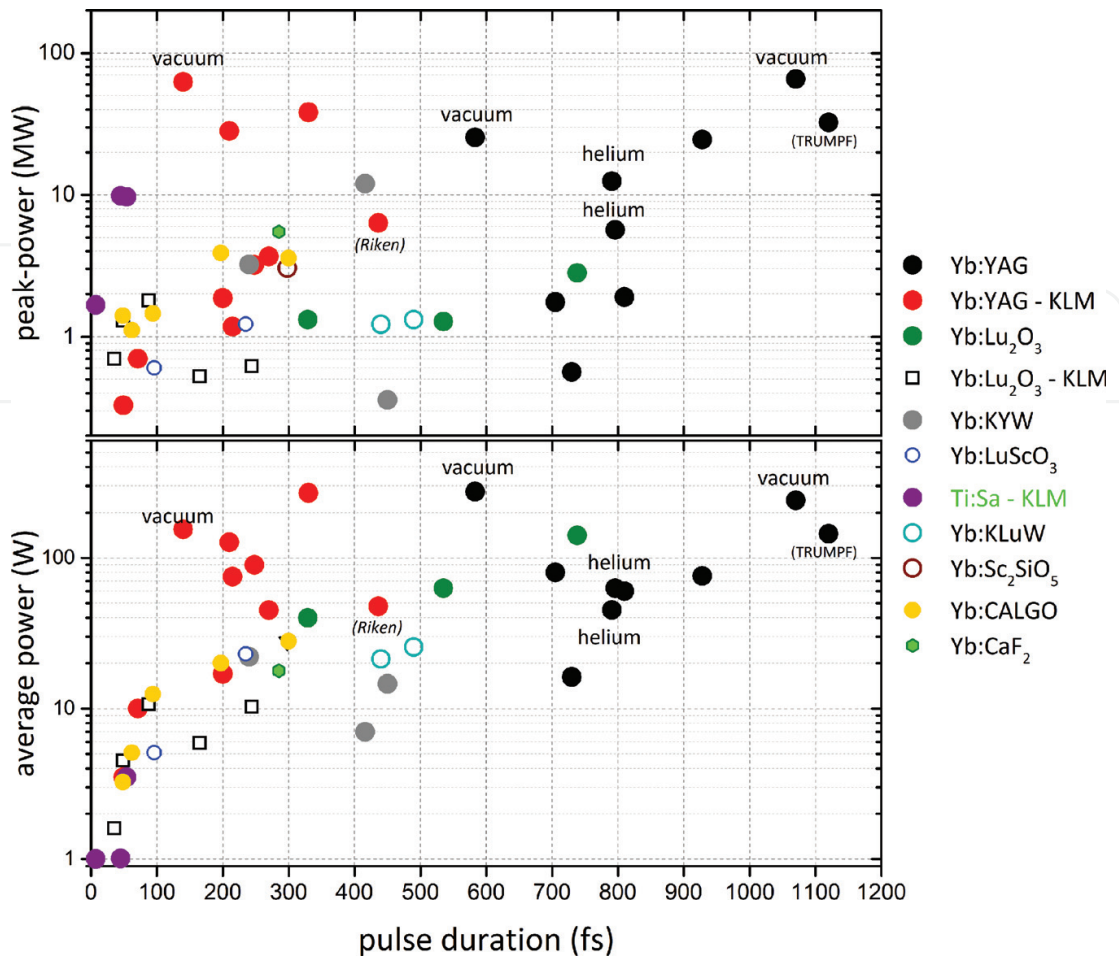
Figure 1. Summary of diverse femtosecond thin-disk oscillators adopted from [26]. More details including the references can be found in [26].
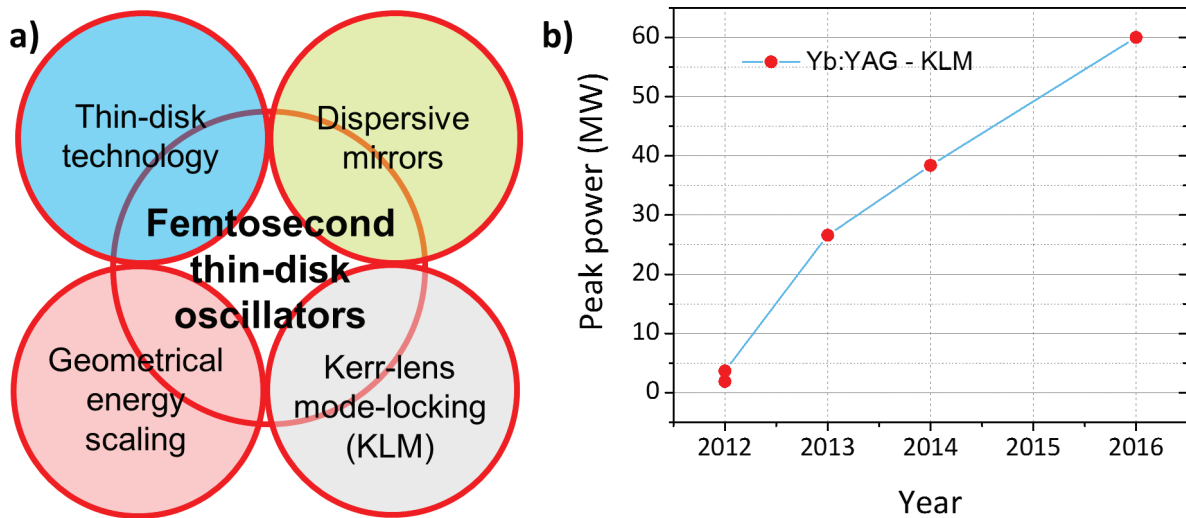

Figure 2. (a) Four key elements: thin-disk technology, dispersive mirrors, Kerr-lens mode-locking and geometrical energy scaling concept form femtosecond thin-disk oscillator technology described and (b) graphical representation of the rapid thin-disk KLM oscillator development in our group.

2. Kerr-lens mode-locking principle

The refractive index n of a material depends on the incident electric field intensity. A Gaussian intensity distribution causes an increase of the refractive index in the central part of the beam relative to its outer regions therefore forming a nonlinear lens. The higher the light intensity, the stronger the action of such a lens. The lens becomes stronger for smaller beam radii ω and media with higher nonlinear refractive index n_2. Self-focusing occurs for a high-intensity, pulsed laser-beam (red, **Figure 3**) and reduces losses due to the hard aperture blocking the continuous wave (CW) beam of lower intensity. In a resonator-cavity, this mechanism initiates mode-locking and acts as an artificial saturable absorber. Catastrophic run away damage can happen when a critical power is reached and the length of the medium exceeds the self-focusing length. The first oscillator working on the KLM principle was discovered by Spence et al. [18] and referred to as self-mode-locking or magic mode-locking. Piche [39] explained the mode-locking mechanism on the basis of self-focusing and only a few authors recognized the potential of the self-focusing effect for mode-locking before the invention of KLM [40, 41]. Since that time, KLM established itself as the method of choice for ultrashort-pulse generation and numerous studies were done on resonator design, theoretical numerical and analytical description of KLM and experiments on ultrashort pulse generation. Mostly, experiments were performed with the Ti:Sa gain medium, which has several outstanding features: an extremely broad gain bandwidth, short upper-state lifetime as well as high thermal conductivity [19]. Understanding that shortest possible pulses can only be obtained when nonlinearities and dispersion are balanced to form so-called soliton pulses [42, 43] preceded the invention of KLM. However, this technique constituted the decisive building-block to enable robust, usable solid-state femtosecond oscillators. With Kerr-lens mode-locked solitonic Ti:Sa oscillators up to several 100 mW average power and up to MW-level peak-power were realized with pulse durations approaching few optical cycles, all in a compact, reliable setup that was superior to the old dye-based technology. This ensured its worldwide adoption in many optical laboratories and nearly immediate commercialization.
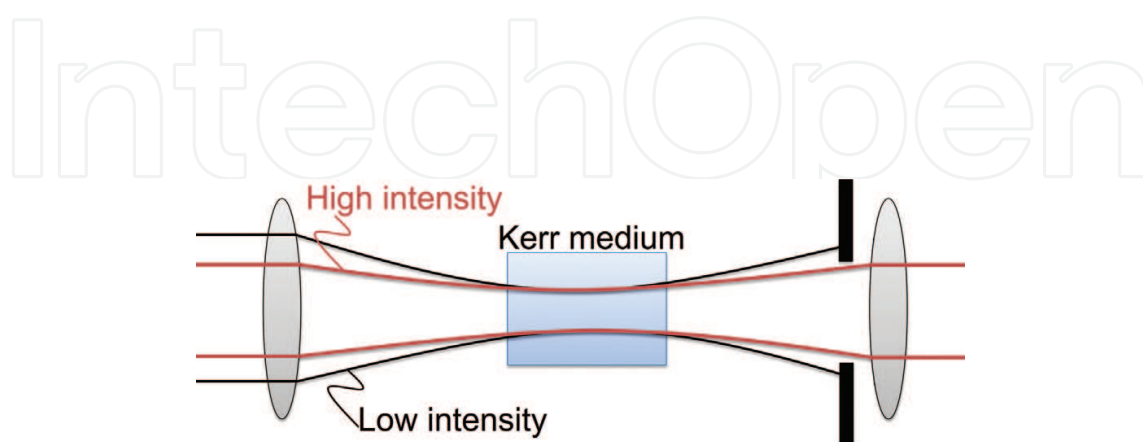

Figure 3. Basic principle of KLM. Self-focusing occurs for a high-intensity beam (red) and reduces the losses due to a hard aperture (two black knifes) blocking the low-intensity (CW) beam. This mechanism initiates mode-locking and acts as an artificial saturable absorber.

3. Power scaling in KLM oscillators

For power scaling of soliton mode-locked oscillators both the nonlinear and the thermal instabilities need to be considered. A thin-disk gain medium is in both cases an ideal solution. The predominantly one-dimensional heat flow within the thin gain medium minimizes thermal lensing and the low peak intensities in the large but thin disk minimize the nonlinear phase shift. Unlike the usual bulk KLM oscillators [44], high power thin-disk KLM oscillators require that the role of the gain and Kerr-medium are separated to distinct intra-cavity elements. This way it is possible to keep the mode size on the thin-disk large and to tune the nonlinear phase shift nearly independently by means of an additional Kerr-medium (see **Figure 4a**).

3.1. Average power scaling

One of the crucial advantages of KLM compared to semiconductor saturable absorbers is nearly negligible linear and nonlinear absorption inside of a dielectric Kerr-medium. SESAMs normally exhibit non-saturable losses and multiphoton absorption [45]. Such low absorption
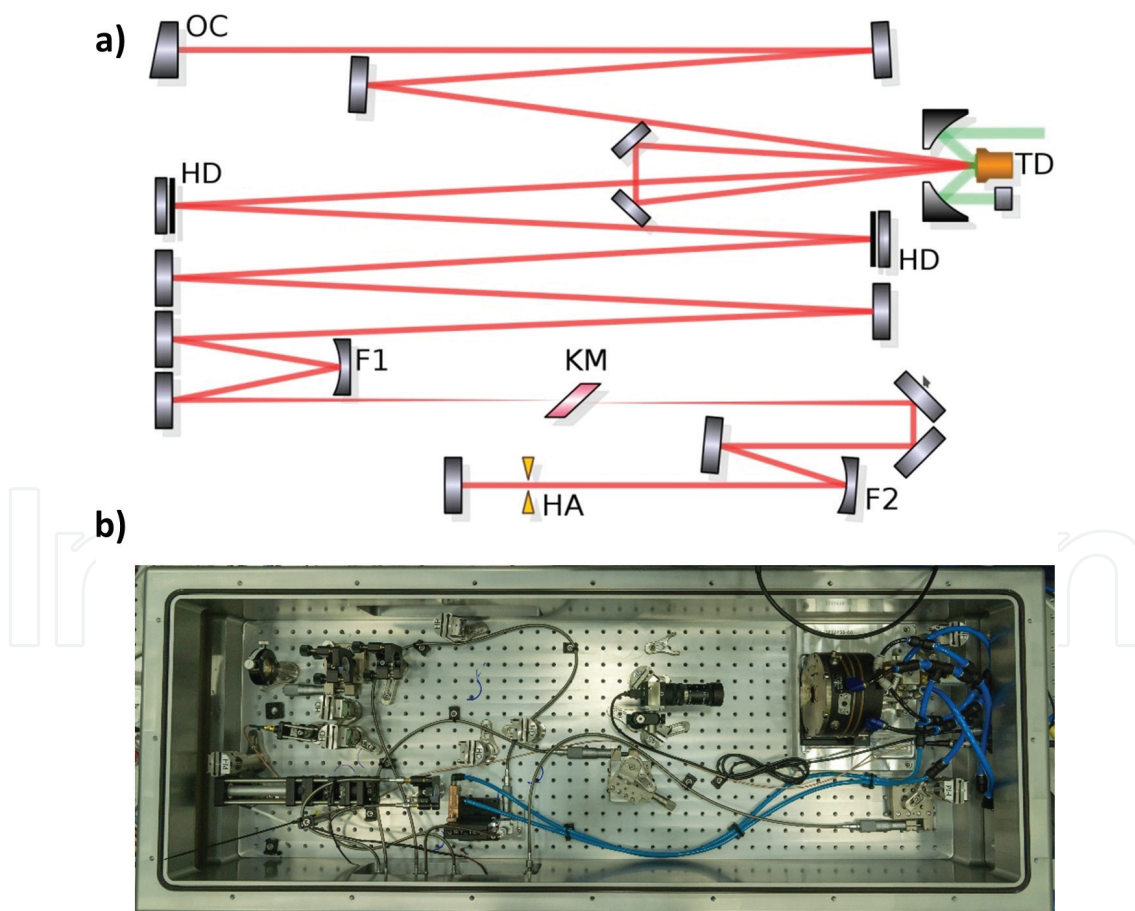

Figure 4. (a) Oscillator sketch. TD: thin-disk; OC: output-coupler; HD: highly dispersive mirrors; $F_{1,2}$: focusing mirrors; KM: Kerr-medium; HA: hard aperture and (b) a photo of a 100 W-level thin-disk oscillator in a compact monolithic aluminum housing. Photo credit: Kilian Fritsch.

losses are essential for average power and peak power scaling. Thus, in 2014, quickly after the first demonstration of thin-disk KLM [33] up to 270 W average power from a KLM thin-disk laser were demonstrated [7] (also see **Figure 2b**). The utilized thin-disk technology remains the key component for high average power operation for both Kerr-lens and SESAM mode-locking techniques. While the first demonstrator of a KLM thin-disk oscillator [33] relied on a copper mounted thin-disk the record performances approaching 300 W output were achieved with a thin-disk contacted to a diamond heat sink [7]. The superior heat-conductivity of diamond in combination with a suitable contacting technique [46] allow both larger pump intensities as well as thinner disks to be used which helps to reduce thermal lensing and aspherical aberrations [47].

Another important aspect is thermal lenses in the oscillator elements. KLM oscillators require an increased sensitivity to the Kerr-lens to initiate mode-locking and retain a strong self-amplitude modulation (SAM) effect. This higher sensitivity is achieved by adjusting the resonator close to the edge of stability [48, 49] where, however, not only the sensitivity to the Kerr-lens but also to any thermal lens inside the resonator is increased. In particular, the Kerr-medium material has a very pronounced influence on the oscillator behavior. For intra-cavity average power levels larger than 500 W, the use of fused silica plates is difficult at best, exhibiting strong thermal lensing. This is observable, e.g., by shifting the Kerr-medium under CW irradiation along the beam-axis and monitoring the mode-size change. Suitable alternatives are found in sapphire (46 W m^{-1} K^{-1} [50]), crystalline quartz (10 W m^{-1} K^{-1} [50]) or YAG (13 W m^{-1} K^{-1} [50]) materials, all having a significantly higher thermal conductivity than fused silica (1.4 W m^{-1} K^{-1}). With a sapphire Kerr-plate more than 1.2 kW, stable average power could be demonstrated inside the KLM oscillator.

Furthermore, highly dispersive mirrors were found to exhibit additional thermal lensing and to prevent average power scaling [47, 51, 52]. However, after a few attempts in manufacturing of those mirrors, it was possible to identify a multilayer design showing no thermal effects and still providing significant dispersion levels around −3000 fs^2 within 10 nm spectral bandwidth [53]. Another thermal lens suppression method implies the use of substrates with higher thermal conductivity and (or) lower thermal expansion coefficients [54, 55].

3.2. Peak power scaling: general aspects

The pulses traveling inside the KLM oscillator cannot take on arbitrary pulse energy E and width T but have to obey the well known soliton propagation law. It is assumed that soliton mode-locking is stable at a certain peak power level P_0 [56] then

$$T = \sqrt{\frac{|\beta_2|}{\gamma P_0}} \tag{1}$$

with the group delay dispersion (GDD) β_2 and the nonlinear self-phase modulation (SPM) coefficient γ. The pulse can retain its shape when the frequency chirp due to SPM is canceled by (anomalous) dispersion of opposite sign. Pulses with a peak-power smaller or larger than P_0 do not meet this condition. If the peak-power is too small, the pulses are dispersed and if it

is too high, several instabilities can occur. Commonly observed instabilities are the splitting into two or more pulses per roundtrip period or the appearance of additional CW-background radiation. This equation describes well the case not only when pulses travel in lossless media such as fibers or a passive resonator but also catches the dilemma of power-scaling in mode-locked oscillators.

The pulse energy of a soliton can be increased, e.g., by introducing larger values of the GDD. New coating methods allow introducing GDD on the order of 100,000 fs^2 with highly dispersive mirrors [7, 30, 57]. However, the larger chirp from the strong dispersion is automatically compensated by a pulse-duration growth that leaves the peak power constant. This way highest pulse energies were generated and extracted from SESAM mode-locked oscillators at the expense of longer pulses [28, 30].

The second important variable in Eq. (1) is the reduction of the SPM parameter which depends on the effective mode-area A_{eff} inside the oscillator elements of thickness d and nonlinear refractive index n_2. Interestingly, a contribution of air to the SPM parameter cannot be neglected anymore at a certain intra-cavity peak power and cavity length.

$$\gamma \propto \frac{d\, n_2}{A_{eff}} \tag{2}$$

A decrease of γ is therefore directly coupled to the resonator geometry, regardless of whether SESAM or a Kerr-lens is used for mode-locking. The thin-disk gain medium favors large beam areas and short crystal lengths for average power scaling which implies also the minimization of the SPM-coefficient γ. Most state of the art, mode-locked thin-disk lasers are operated in a vacuum or reduced pressure environment to further decrease γ [8, 28, 36]. SESAM mode-locked oscillators are especially sensitive to SPM since their modulation-depth and -speed is intrinsically limited for high-power operation. Current limitations to power scaling in such oscillators are assumed to originate partly from the residual nonlinearity in the mirror coatings [45]. KLM oscillators on the other hand appear to have a much higher tolerance to nonlinear phase shifts being attributed to the achievable large modulation depth as well as the near instantaneous response time of the Kerr-nonlinearity. Thus, fairly large peak-powers can be generated even under normal atmosphere [7].

3.3. Geometrical approach to peak power scaling

Increasing the peak-power in KLM oscillators appears straightforward using a geometrical approach. A fair assumption is that the main contribution to the pulse nonlinear phase shift originates from the interaction in the Kerr-medium. Therefore, in an oscillator where all parameters such as dispersion, self-amplitude modulation, losses, pulse duration, etc. are fixed and only the mode area in the Kerr-medium is increased, the peak power should increase linearly with A_{eff}. This is not in contradiction with the soliton condition as stated in Eq. (1). The Kerr-medium is located in the beam waist of a focusing arrangement as seen in **Figure 4**. The mode radius w_{kerr} in the Kerr-medium is linearly dependent on the curvature radius $R_{1,2}$ of the focusing arrangement mirrors F1 and F2. Therefore, varying $R_{1,2}$ by a factor N, one would

expect to increase the peak power favorably by the factor N^2. A necessary condition for this is that SAM also stays constant. This condition, however, is not necessarily fulfilled. Unfortunately, the decisive SAM parameters of a certain KLM resonator such as modulation-depth or saturation-power are not easily measurable and even simulations appear challenging due to the coupling between temporal and spatial extent of the pulses. The dependence of SAM on the resonator geometry therefore gives an experimentally observed deviation from the initially expected, quadratic scaling of the peak power.

The geometrical power scaling concept was applied experimentally as published in earlier work of the authors [7, 8]. The KLM oscillators were operated in air both under normal and reduced pressure environments. For the scaling experiments in work [7], all parameters except the pump power were kept constant. Four passes of the laser mode through the Yb:YAG thin-disk (TRUMPF Laser GmbH) per roundtrip allowed to couple out large fractions of the intra-cavity power (21% transmission of the output coupler). The mode size inside the 1 mm thick sapphire Kerr-plate was varied by successively exchanging the mirrors $F_{1,2}$ to have $R_{1,2}$ ranging from 300 to 900 mm. The resulting peak power increased proportionally to $R_{1,2}$. These results are summarized in **Figure 5**.

As described previously, the soliton peak-power is fairly invariant under a change of the intra-cavity GDD. However, the changes in pulse energy and duration can be substantial and give flexibility in the design parameters. This is demonstrated in **Figure 5b**, where the GDD in the thin-disk KLM oscillator was varied from $-18,000$ to $-48,000$ fs^2 by exchanging dispersive
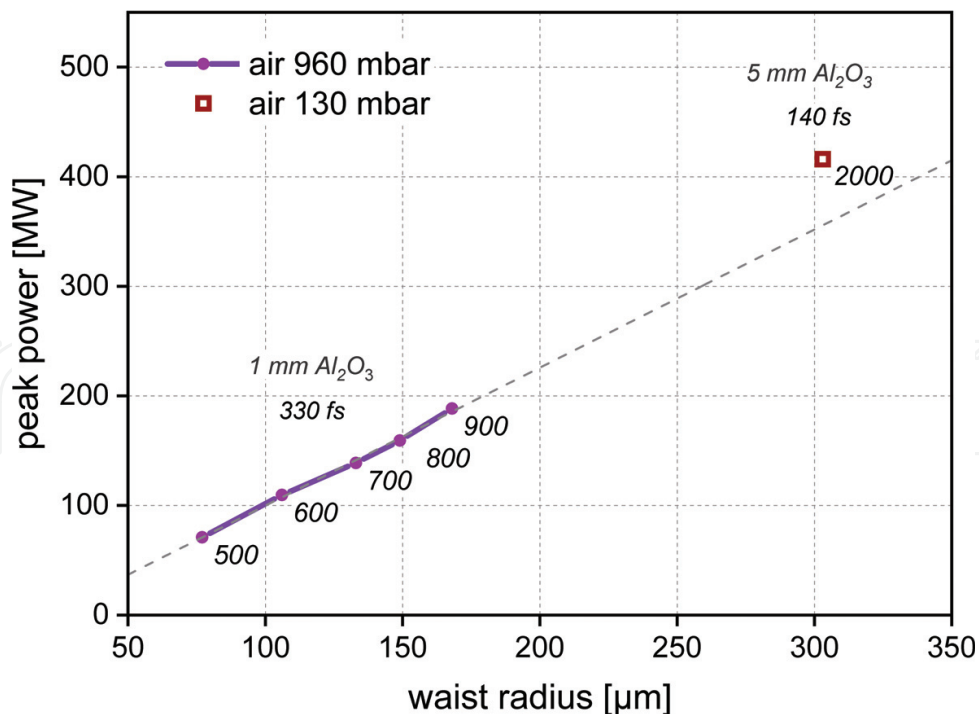

Figure 5. (a) Summary of the data from the geometrical KLM power-scaling approach. The waist radius in the Kerr-medium, growing with $R_{1,2}$, is approximated from ABCD-matrix calculations and (b) experimental example of intra cavity peak power and pulse duration when the total oscillator second order anomalous dispersion (GDD) is increased.
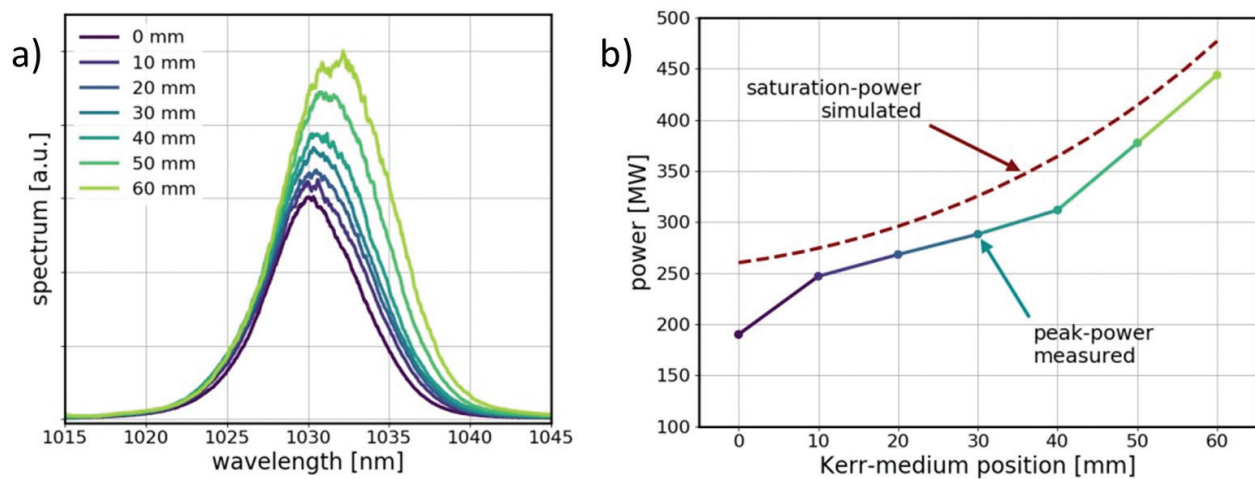
Figure 6. (a) Spectral broadening and spectral shift for different Kerr-medium positions with respect to the focus and (b) intra-cavity peak power for different Kerr-medium positions. The saturation-power of the SAM is also estimated from ABCD-calculations and plotted.

mirrors. In particular example, the intra-cavity pulse energy increased from 32 to 57 µJ while the pulse duration also increased from 210 to 330 fs showing little effect on the peak power.

Soliton mode locking with strong self-phase modulation allows the direct generation of pulses approaching the spectral gain bandwidth of the laser-medium. SPM plays a key role in replenishing those spectral components of the pulse which do not see sufficient net amplification from the gain emission spectrum. A reasonably small value of the intra-cavity dispersion as well as a strong self-amplitude modulation is necessary to reach this regime. In a KLM oscillator combining a fairly low roundtrip GDD of $-12,000$ fs^2 as well as a sapphire plate of 5 mm thickness, 140 fs pulses could be generated with a high optical-to-optical efficiency of 29%. The oscillator operated with a focusing section incorporating mirrors $R_{1,2}$ with 2 m curvature. This allowed an intra-cavity peak-power level of more than 400 MW with more than 60 MW output peak power. These results are in a good agreement with the linear power-scaling curve in **Figure 5a**.

The SAM is quite sensitive to the position of the Kerr-medium within the focus of $F_{1,2}$. Simulations show that mostly the saturation power is affected which intuitively follows from the change of intensity in the medium. Data taken for a Kerr-medium being translated through the focus are displayed in **Figure 6**. It is evident that both the spectral bandwidth and the peak-power increase while the Kerr-medium position is shifted out of the focus. A factor of nearly 2 could thus be gained in intra-cavity peak-power, from near 200 MW to more than 400 MW. Beyond this point mode-locking could not be observed.

3.4. Influence of atmosphere

The relatively short ($\sim$ 5 m) KLM oscillators with $R_{1,2}$ up to 1 m are fairly insensitive to pressure changes of the encompassing air and most of the nonlinear phase-shift is acquired in the Kerr-medium. The increase of Rayleigh distance for weaker focusing (longer $R_{1,2}$) leads to

the increase of nonlinear phase acquired in gas. Thus, the contribution of air relative to that from the bulk Kerr-medium becomes significant. This is potentially harmful as (i) the pulse-stability becomes more dependent on air-fluctuations due to the coupling to SAM and SPM (ii) the oscillator SAM cannot be optimized independently anymore by positioning of the Kerr-medium as the atmosphere begins contributing to the mode-shaping.

This effect can only be counteracted by evacuating or decreasing the pressure of the atmosphere in the oscillator. A rough estimation of the fractional contribution of the bulk Kerr-medium to total nonlinear phase-shift, depending on waist-size of the cavity-mode and different pressure levels is depicted in **Figure 7**.

For these reasons, it was necessary to reduce the atmospheric pressure in the oscillator from [8] to about 150 mbar for stable operation whereas the effect of evacuation proved negligible in the short-$R_{1,2}$ oscillators [7]. The total nonlinear phase-shift acquired in the reduced-pressure oscillator with $R_{1,2}$ being 2 m was approximately 0.6 rad. In that case, the contribution of air to the total nonlinear phase-shift can be estimated to stay favorably below 10%.

Although the geometrical peak power scaling concept described here exhibits a seemingly linear dependence of the intra-cavity peak-power on the mode size in the Kerr-medium, it is very interesting to further verify this dependence for even larger mode sizes and higher intra-cavity peak powers.
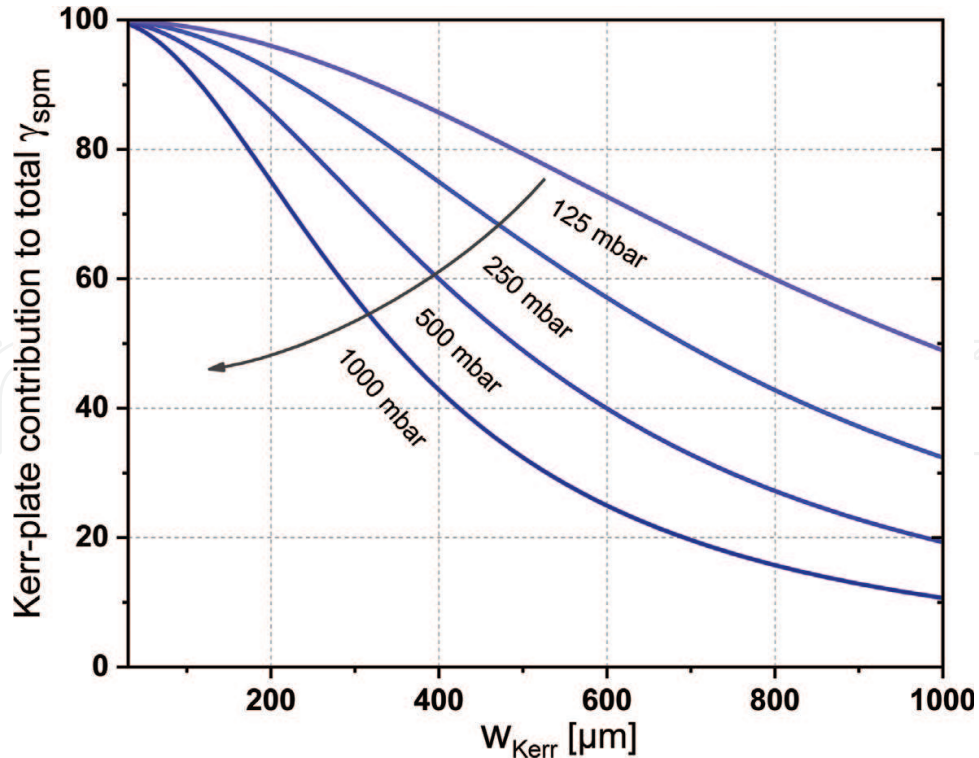

Figure 7. Estimated contribution of the Kerr-plate to the total nonlinearity γ, originating from both the solid Kerr-plate and the air inside the oscillator. It is plotted for different air-pressures.

3.5. Intensity noise and CEP stabilization

Since power-fluctuations can be enhanced in nonlinear processes like SPM, high-harmonic generation, difference frequency generation or optical parametric amplification it is necessary that the pulses generated from the oscillator are as noiseless as possible. It is not obvious that high-power oscillators, especially those with long cavities, can be as silent as usual low power bulk KLM oscillators. Concerns were also raised by some that high-power KLM oscillators would also suffer from instabilities since the initiation of mode-locking requires a setup close to the cavity stability limit. State of the art KLM thin-disk oscillators deliver more than 100 W average power and, thus, are by two orders of magnitude more powerful than usual KLM bulk oscillators. For instance, the oscillator described in the previous section [8] delivers 150 W average and 60 MW peak power.

The intensity noise of this oscillator was characterized (see **Figure 8**). Measurement of the laser output with an RF-signal analyzer reveals that nearly all of the noise is generated in the low-frequency band below 10 kHz. This can be attributed to both technical noise such as water-cooling, pump-source or air-turbulences as well as gain-relaxation dynamics. The latter lies in the lower kHz range due to the approximately 1 ms upper state lifetime of Yb:YAG. An intensity noise of 0.3% rms deviation in the 1 Hz–1 MHz window is typical for KLM thin-disk oscillators. At slightly reduced power levels even better values can be measured on a daily basis. These intensity-noise values are comparable to commercial Ti:Sapphire oscillators and promise good results for CEP stabilization of high peak and average power thin-disk oscillators.

Many advanced scientific applications such as high precision spectroscopy in the XUV-VUV range or attosecond pulse generation require the lasers to be CEP stabilized. Obviously, the demonstration of CEP stabilization of femtosecond thin-disk oscillators is an important step towards enabling these applications with a compact, transportable thin-disk oscillator source. Moreover, a low intensity noise is a critically important prerequisite for the CEP stabilization demonstration. The first carrier envelope offset frequency stabilization of a femtosecond thin-disk oscillator was demonstrated with a KLM thin-disk oscillator providing a remarkably high average power of 45 W and a peak power over 4 MW [58]. A similar demonstration followed with a SESAM mode-locked thin-disk oscillator, providing a moderate output power of only
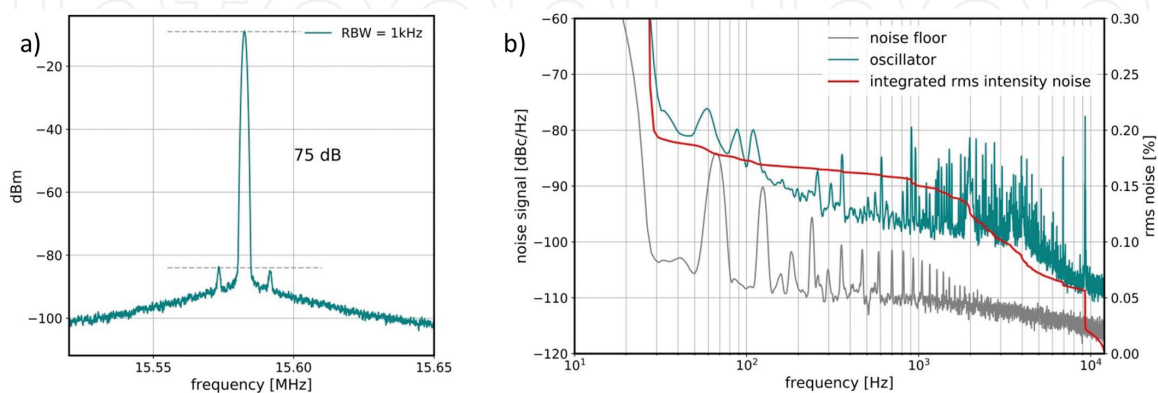

Figure 8. (a) RF signal around the repetition rate of the oscillator with 60 MW output peak power. Small sidebands are visible more than 75 dB below the signal and (b) low-frequency noise performance.

2.1 W [59]. So far, CEP stabilization of high average and peak power oscillators was demonstrated only for KLM thin-disk oscillators resulting in sub-300 mrad out-of-loop noise and output average powers in the 40–50 W range. This was achieved by implementing two CEP control methods, namely intra-cavity loss control by means of an acousto-optic modulator (AOM) [5] and pump-diode control by means of dual-wavelength pumping [60]. Very recently, a new intra-cavity loss modulation approach comprised of an AOM simultaneously acting as a Kerr-medium was implemented [61]. This resulted in the highest average power CEP stabilized laser delivering over 100 W output power and over 30 MW peak power. This approach seems to be scalable by at least an order of magnitude in terms of peak power making it a method of choice for the next-generation CEP-stabilized KLM thin-disk oscillators.

4. Discussion

4.1. Further power scaling opportunities

Even though the geometrical scaling-procedure enables near 100 MW pulses directly from KLM oscillators, it relies on a substantial intra-cavity peak- and average power increase. This raises the demands on the coating damage thresholds during stressful events such as the transition to mode locking. The elevated intra-cavity average powers of more than 1 kW also require careful selection of the utilized materials to prevent thermal lensing instabilities. Complementary to the intra-cavity power-scaling, it is possible to boost the oscillator output by enlarging the output-coupling ratio. This concept has been realized with a mode-locked thin-disk oscillator in [62] for the first time using an imaging multi-pass configuration. Up to 72% of the circulating power were extracted from the SESAM mode-locked oscillator in [30] resulting in 145 W average power output while the intra-cavity value was only 200 W. The short interaction length in the thin disk cannot replenish such high power-loss during a single roundtrip which needs to be overcome by an increased number of beam-passes through the disk, e.g., with an imaging multi-pass cell (20 passes realized in [30]).

The number of disk passes cannot be made arbitrarily high, however, since any thermal lens in the disk is accumulated, giving rise to a narrowing of the cavity-stability zones with respect to the pump power. While this effect has obviously not hindered comprehensive implementation in an oscillator-cavity working at the center of the stability-zone [30], it is not as obvious that the same can be done for KLM-cavities that are more sensitive to the presence of thermal lenses. However, recently a first demonstration of this multi-pass concept in a thin-disk KLM oscillator was realized with six double passes through the thin disk per round-trip resulting in 130 W average and 20 MW peak output power [63]. With respect to a reference oscillator, the peak power did not drop when increasing the output-coupling ratio to 30%, rendering it an encouraging result towards scaling the output coupling ratio to 50%.

4.2. Positive dispersion regime

All oscillators presented (see **Table 1**) were mode locked in the anomalous dispersion regime providing bandwidth limited, unchirped pulses with a well behaved temporal phase.

However, this implies high peak-intensities inside the oscillator cavity and therefore strong nonlinear effects even in air. Other limitations might arise due to damage thresholds of the intra-cavity optics because of the intra-cavity peak intensities approaching several 100 GW/cm^2 and peak fluences up to several 10 mJ/cm^2 or even higher during the pulse build-up phase. Up to now, these high intensities have not posed the major limitation to thin-disk KLM oscillators; however, this situation might change in the future when even higher peak and average powers will be targeted, especially in combination with a compact resonator design. Favorably low intensities can be provided by the pulse formation in the normal dispersion regime (chirped-pulse regime) which was first investigated in Ti:Sa oscillators [64] and is nowadays commonly employed to increase the pulse energies obtainable from fiber oscillators [65]. The pulses that form inside such an oscillator are strongly chirped, resulting in lower peak-powers at the same pulse-energy as compared to the solitons under anomalous dispersion. In contrast to Eq. (1), these pulses theoretically scale better in pulse energy with respect to the dispersion-compensation such that $E \propto |\beta|^2$ [66]. While in Ti:Sa oscillators, this method of mode-locking allowed a major improvement in pulse energy [44, 67], the output from Yb-based mode-locked thin-disk oscillators did not improve over the anomalous dispersion regime [32, 68]. One of the reasons is the relatively narrow emission bandwidth of Yb: YAG and the necessity to introduce an additional spectral filter into the oscillator cavity. This spectral filtering was not performed in the work [68] due to additional complexity, losses and the high intra-cavity average power usually associated with thin-disk lasers. Moreover, no practical demand for the realization of a stable chirped-pulse regime has arisen till today since the limits of the anomalous dispersion regime in mode-locked thin-disk oscillators are not yet explored. However, this situation was different for the Ti:Sa bulk oscillators. Although this chirped-pulse regime appears attractive for power scaling and energy scaling [69], the downside seems an increased demand on the self-amplitude modulation to keep these pulses stable and provide reliable pulse-build-up. Due to the difficulties associated with this reliable pulse-build-up, the positive dispersion regime was not further investigated in thin-disk oscillators. To date the highest peak-powers are obtained from solitonic oscillators working in the anomalous dispersion regime and this situation is unlikely to change until some technical limitations associated with high intra-cavity average power and extremely low repetition rate (very long resonator length) will approached.

5. Conclusion

In conclusion, further average power scaling of Kerr-lens mode-locked thin-disk oscillators will have mainly technical limitations related to the thermal lensing in the dispersive mirrors. This can be circumvented by implementing large beam sizes on the already available dispersive optics and substrates with high thermal conductivity. In principle, the TEM$_{00}$ CW performance of thin-disk lasers can serve as an upper limit for the average power scaling which currently lies well above 1 kW [70].

Peak power scaling of this technology is already facing the complications that are related to a reduced air pressure environment, however, these can be to a large extend circumvented by the implementation of the active multi-pass scheme and increased output coupling ratios. However, this limitation is rather technical and does not set a fundamental limit towards output peak powers in the GW range. The geometrical energy scaling concept described in combination with the intrinsic advantages of the KLM technique provides this peak power scalability nonetheless, at the expense of reduced ambient pressure. A limitation that is more fundamental will be due to the difficulties to initiate mode-locking. In other words, one single mode-locking element has to support starting from nearly zero peak power inside of the oscillator while also needing to provide stable mode-locked operation at intra-cavity peak powers exceeding $\sim$10 GW, thus, covering a huge peak power range. These demands on starting and running stably are rather contradictive, rendering this limitation intrinsic to all types of mode-locked oscillators.

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