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Frontiers in passively mode-locked high-power thin disk laser oscillators

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Abstract: Semiconductor saturable absorber mirror (SESAM) mode-locked thin disk lasers define the state-of-the-art performance for high average power and high pulse energy femtosecond laser oscillators. To date pulse energies above 30 µJ and average powers above 140 W have been demonstrated. In this paper we review the achievements of mode-locked thin disk lasers in terms of average power and pulse energy. Stable mode locking requires single transverse mode operation even at the highest average power, which is challenging and therefore addressed in more detail. We then summarize our expectations on the main challenges and limitations for the next generation of mode-locked thin disk laser oscillators with an average power above 500 W and pulse energies in excess of 100 µJ.

OCIS codes: (140.3580) Lasers, solid-state; (140.4050) Mode-locked lasers.

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1. Introduction

Today, ultrafast laser sources are indispensables tools in science and industry. They offer a versatile and reliable way for materials processing with unprecedented speed and accuracy. Focused single laser pulses can reach intensities that allow to access highly nonlinear processes in atoms and molecules [1, 2]. One important example is high harmonic generation (HHG), where the driving laser light can be converted to shorter wavelengths reaching down to the vacuum ultraviolet (VUV) and extreme ultraviolet (XUV) spectral range that is not covered by a direct solid-state laser transition known to date [3, 4]. Currently, the working horse for many of these high field physics experiments are Ti:Sapphire amplifier systems [5]. The unique broadband emission of this laser material supports the generation of pulses in the sub-10 fs regime [6], which has not been achieved with any other laser material today. However, spectroscopic and crystallographic properties of Ti:Sapphire restrict the achievable average power levels to a few tens of watts of average power; i.e. the required peak power for high field physics experiments can only be achieved at repetition rates in the kilohertz regime. From a technical point of view, many of these experiments could be driven at higher speeds, which would lead to shorter measurement times, a better signal to noise ratio and a higher average photon flux in the case of HHG. In order to achieve the required intensities at megahertz repetition rate an average output power of several hundred watts is required.

The elegance and simplicity of SEmiconductor Saturable Absorber Mirror (SESAM) mode-locked lasers [7, 8], particularly combined with diode-laser-pumped schemes developed during the 1990s, has resulted in new practical, commercially available ultrafast laser systems [9]. These laser systems are being used extensively in applications of ultrafast laser systems, where expensive, power-hungry, maintenance-intensive lasers are being replaced [10]. The field of ultrafast high average power laser sources is mainly dominated by three competing technologies – fiber amplifiers, Innoslab amplifiers and thin disk lasers. An average power of 830 W has been achieved from a fiber amplifier system with a pulse duration of 640 fs [11]. Another approach are Innoslab-based amplifiers that have recently surpassed the kilowatt level with 1.1 kW of average power and a pulse duration of 615 fs [12]. However, these two technologies are based on a master oscillator power amplifier scheme, where the amplifier section usually consists of a chain of several amplifier stages making the overall system complex. In order to reduce complexity and increase reliability, significant research has been focused on the development of oscillators that can provide comparable power levels without additional amplification. The most promising oscillator technology for these power levels is the thin disk laser [13]. To date, a maximum average output power of 141 W in 738 fs long pulses has been achieved using this approach [14].

In this paper we review the development and progress of mode-locked thin disk oscillators in the past decade. The latest achievements in terms of average power and pulse energy as well as their limitations will be discussed. We will also give future perspectives and guidelines in order to complete the next steps in average power and pulse energy scaling.

2. Overview mode-locked thin disk lasers

In this section we discuss the fundamental principle of the thin disk laser. We give a short overview of different thin disk materials, their advantages and drawbacks as well as the results that have been achieved with them in mode-locked operation.

Average power scaling requires improved heat removal and therefore the surface to volume ratio of the gain medium has to be optimized. This can be accomplished with the thin disk, fiber or slab geometry. The thin disk laser approach is based on a gain material that has the shape of a thin disk with a highly reflective (HR) coating on one side and an anti-reflective (AR) coating on the other side for both pump and lasing wavelength [15]. This disk shaped laser crystal has a typical thickness of 100 µm to 400 µm and a diameter of several millimeters up to centimeters. In contrast to bulk oscillators, the thin gain medium leads to outstanding heat removal capabilities and negligible nonlinearities, a crucial point for power and energy scaling of femtosecond oscillators.

Efficient heat removal is possible by mounting the HR side of the disk onto a heat sink (typically copper or diamond) that can be cooled with water. This leads to a nearly one-dimensional heat flow along the beam axis and therefore introduces only small thermal distortions and aberrations. On the other hand, such a thin disk sets certain requirements for the gain medium, not only in terms of mechanical robustness for the fabrication process but also concerning its spectroscopic properties for efficient laser operation. The material should support high doping concentrations and large absorption cross-sections for efficient pump absorption in a multi-pass pumping scheme as suggested by Giesen et al. [15]. Furthermore, a broad gain bandwidth is required in order to support short pulses in mode-locked operation [16].

The most widely-used gain material for thin disk lasers is Yb:YAG [17]. It can be grown with excellent quality and in almost arbitrary sizes. It further shows a good thermal conductivity (typically around 7 W/(m·K) for an Yb^{3+} doping concentration of 3 at.%) which is another key ingredient for laser operation at high power levels. Little surprising, the first mode-locked thin disk laser oscillator was based on Yb:YAG. It has been presented in 2000 and delivered an average power of 16.2 W with a pulse duration of 730 fs [18]. Four years later the average power could be increased by almost a factor of five to 80 W with a very similar pulse duration of 705 fs [19]. Only this year an average power of 100 W has been surpassed with an Yb:YAG thin disk laser that achieved an average output power of 108 W and a pulse duration of 1040 fs [20]. To date, the typical pulse duration of high power SESAM mode-locked Yb:YAG thin disk lasers has been limited to about 700 fs, even though low power SESAM mode-locked laser oscillators demonstrated much shorter pulses [21, 22]. Very recently, the first Kerr-lens mode-locked (KLM) Yb:YAG thin disk laser has been presented with an average power of 17 W and a pulse duration of 200 fs [23].

Applications such as attosecond science using HHG have been one of the motivations to look for different thin disk laser materials that can support sub-100 fs pulses [24]. One broadband material that has held the record for the shortest pulses for many years was Yb:KYW [25, 26]. In 2002, a mode-locked thin disk laser based on this material was presented with an average power of 22 W and a pulse duration of 240 fs [27]. The varying quality of the available material and the monoclinic nature of this crystal, however, limited the progress towards further power scaling.

Besides the tungstate materials, some borate materials show very promising gain spectra for the generation of short pulses [28, 29]. Some initial mode locking experiments with Yb:YCOB revealed a pulse duration of 270 fs at a still moderate average output power of 2 W. Similar to Yb:KYW anisotropic thermal aberrations complicated fundamental mode operation at higher power levels [30].

Finally, another very successful group of thin disk gain materials are the Yb-doped cubic sesquioxides [31–37]. The most promising representative in terms of average power scaling is $Yb:Lu_2O_3$ (Yb:LuO). It shows a higher thermal conductivity (around 11 W/(m·K) for an Yb^{3+} doping concentration of 3 at.%) than Yb:YAG and an about three to four times higher absorption cross-section at the zero-phonon line (976 nm) than Yb:YAG at its typical pump wavelength of 940 nm. This does not only allow the fabrication of thinner disks but also reduces the thermal load in the crystal as the quantum defect is about 38% lower. Even though these cubic sesquioxide materials are known since 1957 [37], the rather high melting temperature of about 2400°C prevented the growth of high quality crystals of the size required for thin disk laser operation. Only in 2007 the solid-state laser group at the ILP in Hamburg optimized the heat exchanger method [36]. This allowed them to grow these materials in excellent quality and sufficient size. Their Yb:LuO thin disk laser crystals showed a record high optical-to-optical efficiency of 73% at an output power of 301 W in multi-mode cw operation [38]. The first mode-locked thin disk laser based on this material was presented in

2007 and delivered an average power of 25 W with a pulse duration of 523 fs [39]. Subsequent power scaling by increasing the pump spot size on the disk led to a maximum average output power of 141 W in 738 fs long pulses, which is to date the highest output power reported from a mode-locked oscillator [14]. The optical-to-optical efficiency of over 40% was higher than typically reported for mode-locked Yb:YAG thin disk lasers. Only this year a low power Yb:LuO thin disk laser achieved a pulse duration of 142 fs exploiting the twice as broad gain bandwidth of Yb:LuO in comparison to Yb:YAG [40].

For the generation of even shorter pulses the same research group at the ILP in Hamburg developed the stoichiometric mixture of Yb:LuO and Yb:ScO_3 (Yb:ScO) resulting in Yb:$LuScO_3$ (Yb:LuScO) [41]. This material succeeded in combining the two gain spectra of Yb:LuO and Yb:ScO that lie roughly 7 nm apart to a 22 nm broad gain bandwidth centered around 1038 nm. The first crystal tested in mode-locked operation was only of compromised quality, which explains the limited average power of 7.2 W. Nevertheless this material took over the record in terms of short pulse duration from Yb:KYW (240 fs) with a pulse duration of 227 fs in 2009 [42]. In the meantime Yb:LuScO crystals of excellent quality are available and average power scaling to 23 W with pulse duration of 235 fs has been demonstrated [43]. Very recently a SESAM mode-locked thin disk laser based on this material achieved a pulse duration of below 100 fs for the first time [44]. The average output power was 5.1 W. In contrast to Yb:KYW this material has an isotropic crystal structure and further power scaling can be expected in the near future. The approach of mixing different sesquioxide materials continued to Yb:$(Sc,Y,Lu)_2O_3$ (Yb:ScYLO) which is the combination of Yb:ScO, Yb:YO and Yb:LuO. However, this material does not show any spectroscopic advantages over Yb:LuScO and first mode-locking results with 3.9 W of average power and a pulse duration of 236 fs did not encourage further investigation of this material [45].

Table 1 summarizes laser results achieved to date from SESAM mode-locked thin disk laser oscillators. A more general overview of different thin disk materials also in terms of their cw performance but with a particular focus on the minimum achievable pulse duration is given in reference [24].

Table 1. Overview of SESAM mode-locked thin disk lasers. It lists the average power (P_{av}), repetition rate (f_{rep}), output pulse energy ($E_{p,\,out}$), intracavity pulse energy ($E_{p,\,in}$) and the pulse duration (τ_p)

Material	P_{av} (W)	f_{rep} (MHz)	$E_{p,\,out}$ (µJ)	$E_{p,\,in}$ (µJ)	τ_p (fs)	Ref
Yb:YAG	108	3.5	30.7	51.2	1040	[20]
	80	57	1.4	15.6	705	[19]
	76	2.9	25.9	33.2	928	[46]
	63	12.3	5.1	51	796	[47]
	60	34.3	1.7	18.9	810	[48]
	45	4	11.3	113	791	[49]
	16.2	34.6	0.5	9.1	730	[18]
Yb:LuO	141	60	2.4	26.7	738	[14]
	63	81	0.8	14.8	535	[50]
	40	81	0.5	11.1	329	[50]
	24	65	0.37	7.1	523	[39]
	20.5	65	0.32	6.2	370	[39]
	7	64	0.11	2.7	142	[40]
Yb:KLuW	21.3	34.7	0.6	10	440	[51]
Yb:YCOB	2	19.7	0.1	4.5	270	[30]
	4.7	24.4	0.2	14.3	455	[30]
Yb:ScYLO	3.9	36.5	0.1	2.5	236	[45]
Yb:KYW	22	25	0.9	16.4	240	[27]
Yb:LuScO	7.2	66.5	0.1	2.4	227	[42]
	23	70	0.3	6	235	[43]
	9.5	70	0.1	3.8	195	[43]
	5.1	77.5	0.07	2.5	96	[44]

3. Frontier in average power

Power scaling of thin disk lasers can be achieved by increasing both the pump power and the pump spot size at constant pump intensity. A constant pump intensity in the one-dimensional heat flow approximation does not increase the thermal load per unit area, as the cooling surface is also increased by the same amount. This scaling method has already been demonstrated successfully in the past and theoretical limits have been discussed in [13]. For very simple resonators where the output beam quality is not of primary importance this scaling law works almost without any restrictions. However, when it comes to fundamental mode operation some stability considerations have to be taken into account. In 1987 V. Magni investigated stability zones for resonators containing a variable lens [52]. He found that the tolerable variation of this lens – in the case of a thin disk laser this is equivalent to the thermal lens of the disk – is inversely proportional to the square of the minimum spot size on this lens given by the cavity design. For fundamental mode operation this minimum spot size should correspond to the pump spot diameter on the disk. This behavior is illustrated in Fig. 1, which clearly shows the reduced resonator stability zones with increasing pump spot diameters ranging from 1 mm to 4 mm.

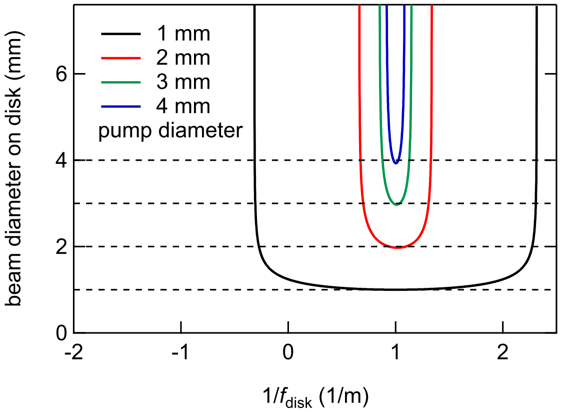

Fig. 1. Simulations of resonator stability zones for different pump spot diameters ranging from 1 mm to 4 mm. The width of the stability zone decreases inversely proportional to the square of the minimum cavity mode size in this zone, which typically corresponds to the pump spot diameter.

It can be clearly seen that a resonator with a pump spot size of 4 mm is much more sensitive to a small amount of thermal lens in the disk than for instance a resonator with a pump spot diameter of 1 mm. The thermal lensing of a thin disk crystal is an accumulated effect of different thermally induced effects like a temperature dependence of the refractive index (dn/dT), bulging or stress due to the thermal expansion of crystal and heat sink, respectively. Whereas some parameters are strictly determined by the gain material employed in the thin disk laser, others can be influenced by the choice of the mounting technique and the material of the heat sink. Standard mounting on copper heat sinks is often achieved by metallizing the HR coated side of the thin disk and using an indium-tin solder. For Yb:YAG, heat sinks from copper-tungstate alloys (CuW) with matched thermal expansion coefficients have been developed. Contacting Yb:YAG onto these heat sinks with indium-gold solder has shown good results [13]. Of course, regarding efficient heat removal a heat sink with a higher thermal conductivity is favorable. Therefore, a procedure has been developed to glue the disk directly on diamond heat sinks [53]. The combination of thin disks and a very thin layer of glue can result in a very stiff compound that shows only very little variation in dependence of the incident pump power. On the other hand, the glue does not yield to any thermal stress and fatal breaking can occur if the temperature gradients within the disk or the temperature difference between disk and heat sink become too large.

Figure 2 shows the curvature of the disk in dependence of increasing pump power (without laser operation) measured with an interferometer. It compares gold-tin soldered Yb:YAG crystals with a thickness in the range of 180 µm to 280 µm on CuW heat sinks with a Yb:YAG disk with a thickness of 100 µm and Yb:LuO disk with a thickness of 150 µm glued on a diamond heat sink. All Yb:YAG disks presented here were pumped at 940 nm. The LuO disk was pumped with a Volume Bragg Grating stabilized pump diode at 976 nm. Unfortunately, we did not have exactly the same disk parameters for these measurements but it is clearly visible that the glued disks on diamond exhibit a nearly constant thermal lens over a large pump intensity range. For all these measurements, we used 24 pump passes through the disk. Due to different doping concentrations, a comparable absorption was achieved in the samples with different thicknesses, ensuring >95% absorption of the pump radiation. The 100 µm thick glued Yb:YAG disk shows no variation within the measurement accuracy of 0.01 m^{-1} for a pump power intensity between 0 and 2.5 kW/cm^2 whereas the thicker Yb:YAG disks (180 µm to 280 µm) on copper-tungstate heat sinks show a variation of about 0.16 m^{-1} in the same range of pump power intensity. This variation is already sufficient to prevent fundamental mode operation over the whole pump power range for a pump spot diameter of 4 mm. In this case, additional adjustments in the cavity would be required when the pump power is increased, such as for example adaptable mirrors [54] or an adaption of the cavity lengths to shift the center of the stability zone [14].

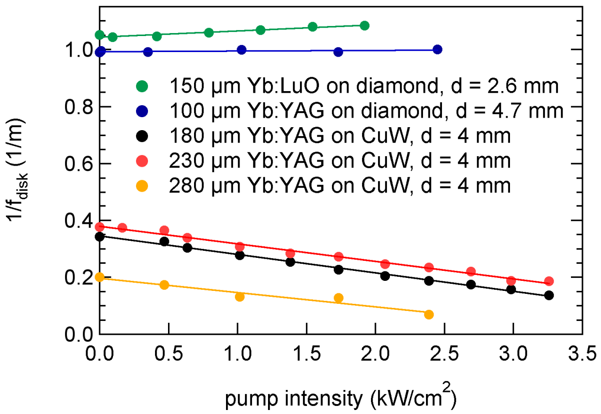

Fig. 2. Interferometric measurements of the equivalent thermal lens with a focal length f_{disk} for differently mounted Yb:YAG and Yb:LuO crystals. The strength of the thermal lens is given in diopter units (i.e. 1/m). It can be seen that the combination of thin crystal thicknesses and mounting on diamond heat sinks results in a very stiff compound that shows almost a constant thermal lens with increasing pump intensity. The disk mounted on diamond have a pre-curvature with a radius of approximately 2 m whereas the disks soldered on CuW have a pre-curvature of approximately 5 m in radius.

In contrast to our previous result [14] the Yb:YAG disk on diamond supports cw fundamental mode operation up to 430 W (pump power limited) without any adjustments in the cavity. The pump operated at a wavelength of 940 nm and the corresponding incident pump power level was 830 W. Taking into account the extracted laser radiation, this corresponds to a pump power density on the disk of approximately 2.3 kW/cm^2. A perfect beam quality was achieved over the full pump power range (pump spot diameter was 4.7 mm). Figure 3 shows an M^2 measurement and the beam profile at the highest output power. The obtained beam quality suggests that no significant aspherical aberrations occur at these high power levels. Comparable CW power levels at good beam quality has been reported in references [55, 56].

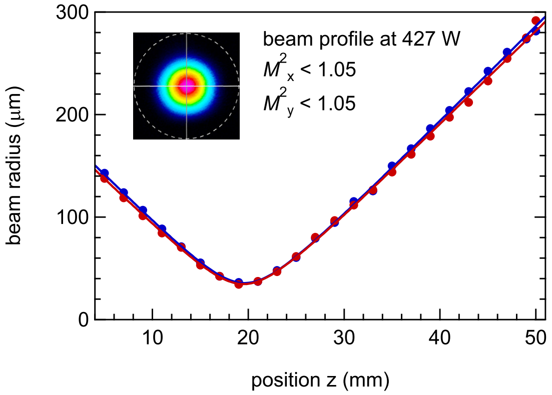

Fig. 3. 100 µm thick Yb:YAG disk on diamond: measurement of the beam quality in continuous wave operation. We measured an M^2 of below 1.05 for both beam axis and an ideal Gaussian intensity distribution (inset picture) at the maximum output power of 427 W with a pump spot diameter of 4.7 mm.

Single transverse mode operation is one key requirement for stable mode locking and a fundamental Gaussian beam (TEM_{00}) provides the highest peak power. The demonstrated 430 W of cw output power in TEM_{00} is very promising for the next step in average power scaling in mode-locked operation. A recent study showed that the SESAMs can withstand the required intracavity intensities. An optimized design did not show damage up to a pulse fluence in excess of 0.21 J/cm^2 and a peak intensity of 370 GW/cm^2 [57].

4. Frontier in pulse energy

In the previous section, we discussed the challenges for fundamental mode operation of high power thin disk lasers. In this section, we focus on the challenges for pulse energy scaling.

In case the available pump power or the power in fundamental mode is limited, the pulse energy can be further increased with a reduction of the pulse repetition rate. In a fundamentally mode-locked oscillator the pulse energy (E_p) is given by the average power (P_{av}) divided by the repetition rate (f_{rep}), i.e. $E_P = P_{av} / f_{rep}$. Typically, mode-locked thin disk lasers operate at a repetition rate between 50 MHz and 80 MHz given by a practical cavity design for pump spot diameters between 1.2 mm and 3 mm. Much smaller pulse repetition rates can be achieved for instance with a 4-*f* extension or a Herriott-type multi-pass cell [58] which are particularly convenient as they do not change the *q*-parameter of a Gaussian beam in one roundtrip. This means that they can be added modularly to the cavity without changing the initial cavity design. Those two techniques have already successfully been applied to reduce the repetition rate from a 60 MHz oscillator down to 4 MHz and allowed a pulse energy increase from 1.4 µJ to 11.3 µJ [47, 49].

With increasing pulse energy SESAM and dispersion parameters need to be adapted. The higher pulse fluence on the SESAM has to be compensated either with a larger spot size on the SESAM or with an adapted SESAM design with a higher saturation fluence. Up-to-date, SESAMs have not limited average power and pulse energy scaling of modelocked thin-disk lasers. In particular the recent development of optimized high damage threshold SESAMs with extremely low nonsaturable losses confirmed this point by enabling record-high average power and energy levels [14, 20]. We refer to references [43, 57, 59] for a more detailed study on suitable SESAM designs for high power and high energy mode-locked oscillators. In the future, kW-level ultrafast oscillators might require even further optimized designs with optimized thermal management and studies on the influence of surface aberrations.

In addition to the SESAM parameter, the dispersion management also has to be adapted. In a soliton mode-locked laser the pulse duration is given by the interplay of self-phase modulation (SPM) and negative group delay dispersion (GDD) as long as the targeted pulse duration is supported by the gain and the dynamics of the absorber [60, 61]. The negative GDD is usually introduced by GTI-type mirrors [62] which is intensity independent. In contrast, SPM is an intensity dependent effect and therefore increases with increasing pulse energy. Compensating the increased SPM with an increased GDD by adding more GTI-type mirrors becomes impractical as every additional mirror needs space and introduces losses. Therefore stable high peak intensity operation ultimately requires additional measures to reduce SPM.

One approach to reduce the SPM is an increase in pulse duration, like for instance with a resonator operated in the positive dispersion regime [51, 63]. However, most applications benefit from the stability of soliton mode-locked lasers and shorter, compression-free pulses.

In a typical cavity for a soliton mode-locked thin disk laser the circulating pulse experiences SPM by passing through nonlinear materials like the gain medium, a Brewster plate and the air atmosphere. The SPM from the disk can typically be neglected as the mode size on the disk is large and the pulse passes only through very little material. The influence of the Brewster plate can be controlled by the choice of the thickness and the mode size at the location in the cavity where it is placed. Removing the Brewster plate is usually not desirable as it offers some control over the total amount of SPM and maintains linear polarization of the laser output. The contribution of the air atmosphere has been ignored initially. All earlier attempts to increase the pulse energy have been prevented by the significant nonlinearity in air, which was initially not recognized as the limiting cause. Once air in the resonator was identified as the most significant contributor to the total SPM and was replaced with helium which has a much smaller nonlinear refractive index than nitrogen [64] the next milestone of 10-μJ pulse energy was achieved. This resulted in a pulse energy of 11 μJ and an average power of 44 W from a SESAM mode-locked Yb:YAG thin disk laser [47, 49].

Another approach to reduce to the SPM in the cavity and therefore reduce the amount of the required GDD is to reduce the intracavity power by choosing a higher output coupler transmission. This has the additional advantage that the fluence on the SESAM and the thermal load on all intracavity components is reduced. Efficient laser operation with a higher output coupling transmission is only possible if the gain per cavity round trip is increased accordingly. This can be achieved with a combination of several laser heads in one cavity or with an active multi-pass scheme i.e. several passes over the same disk in one cavity roundtrip. The combination of several laser heads in one cavity has already been demonstrated [13]. However, it is not straightforward to achieve fundamental mode operation as each disk can show a different thermal lensing behavior. The second approach of an active multi-pass cell in a mode-locked thin disk laser has been introduced by Neuhaus et al. [46, 65]. The 26 passes through the gain medium allowed for an output coupling rate of 78% and an average output power of 78 W at a repetition rate of 2.9 MHz. This corresponds to a pulse energy of 26 μJ. In the meantime, this result has been improved to an average power of 108 W with a pulse energy of 31 μJ using a 60% output coupling transmission [20]. The intracavity pulse energy was still below 52 μJ and with a total GDD of $-236000\ \mathrm{fs}^2$ operation in air was possible. In contrast, the 11-μJ pulses in helium – corresponding to an intracavity pulse energy of 113 μJ – could be realized with more than 11 times less negative GDD ($-20000\ \mathrm{fs}^2$). In addition, 26 passes through the thin disk significantly increase the demands on the disk. Figure 4 shows how the thermal lensing stability zones decrease with an increasing number of passes over the disk. The comparison between a single pass (i.e. two passes in one roundtrip, black line) and five passes over the disk (blue line) reveals a shrinking of the overall stability zone by a factor of about five.

For further average power scaling the pump spot diameter has to be increased as discussed in the previous chapter. This sets severe demands on the applicable thin disk crystal properties and mounting techniques. Taking into account the narrower stability zones for multiple passes over the disk (Fig. 4), it seems more likely that the next step towards several hundred watts of average power with pulse energies in the order of 100 μJ or more will be achieved with a single- or only a few-pass resonator in a helium atmosphere or even vacuum.

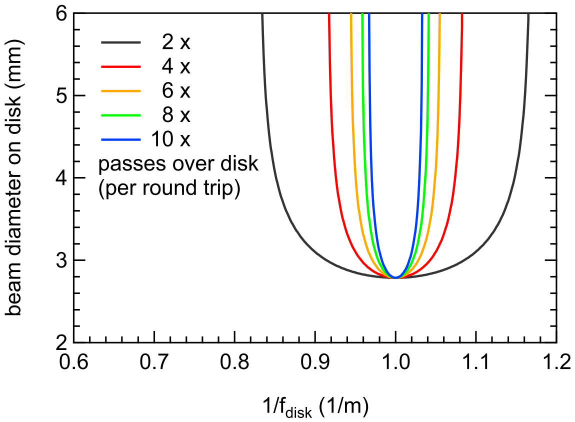

Fig. 4. Simulations of the stability zones of an active multi-pass resonator for different numbers of passes over the disk. This graph compares the stability zones from a single pass (i.e. two passes in one round trip, black line) up to 5 passes (blue line).

5. Conclusion

In this paper we reviewed the development and the current status on SESAM mode-locked thin disk lasers. Today, laser oscillators based on this technology generate average powers above 140 W and pulse energies in excess of 30 µJ.

We discussed the challenges to complete the next steps in average power scaling towards >500 W of average output power and >100 µJ of pulse energy. Thin disk lasers offer excellent heat management and scalability in output power by increasing the pump spot diameter. Nevertheless, special attention has to be paid to the thermal lensing of the disk. The cavity stability zone with respect to a thermal lens significantly reduces with an increasing mode size on the disk. Interferometric measurements of Yb:YAG disks have shown that disks mounted on diamond heat sinks show much less thermal effects than disks soldered on CuW heat sinks. With a state of the art Yb:YAG disk mounted on diamond, we achieved cw fundamental mode operation over the whole pump power range up to an output power of 427 W without any additional adjustments to compensate the increasing level of the thermal lens. With the availability of these disks average power scaling in cw mode-locked operation to the multi-hundred watts regime can be expected in the near future.

Finally, we discussed the progress in terms of pulse energy scaling. So far, there have been two different approaches how to deal with the intracavity SPM at high pulse energy levels. One approach has reduced the SPM by operating the laser in vacuum or a helium atmosphere and therefore eliminating the SPM contribution of the ambient air. Another approach has used an active multi-pass cell that leads to a higher gain per roundtrip. In this case a higher output coupling transmission can be applied which reduces the intracavity pulse energy. We have shown that the latter approach increases the demands on the thermal properties of the thin disk as the stability zone shrinks with every additional pass through the disk. However, at this point both approaches do not show any severe limitations and pulse energy scaling towards the 100-µJ level can be expected from either or even a combination of the two.

Acknowledgment

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