Power and energy scaling of Kerr-lens mode-locked thin-disk oscillators

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Abstract

The goal of this contribution is to provide a guideline for Kerr-lens mode-locking (KLM) of thin-disk oscillators. This includes cavity design, hard and soft-aperture optimization, handling of thermal effects in intra-cavity optics as well as methods of average power and energy scaling. The main differences and similarities between mode-locking of Ti:sapphire bulk and Yb:YAG thin-disk oscillators are presented .

Keywords: (140.3480) Lasers, diode-pumped; (140.3580) Lasers, solid-state; (140.4050) Mode-locked lasers

1. INTRODUCTION

There are several approaches to increasing the energy and average power of a femtosecond laser oscillator. The most common and straightforward approach is to use amplifiers such as fiber, innoslab and thin-disk amplifiers [1-4]. The use of amplifiers adds additional complexity, noise and, not least, costs. Another approach is to use enhancement cavities which allow “storage” of the laser radiation inside of a passive cavity [5, 6]. The range of applications for enhancement cavities is rather narrow due to the fact that they can tolerate only small losses. So far these cavities are mostly used for high harmonic generation, a low efficiency (losses) nonlinear process. Enhancement cavities require precise locking of the repetition rate of the oscillator and its carrier envelope offset frequency (CEO) which adds additional complexity to the system [7]. A third possibility is to directly scale the power and energy of the laser oscillator. This route demonstrated exciting progress over the recent years with peak powers in the range 10-100 MW, obtainable directly from oscillators, which corresponds to even higher intra-cavity peak powers, typically by a factor 5-10 [8-12]. Interestingly, such high peak powers are achieved in the anomalous dispersion regime (ADR), thus the scaling potential of the normal dispersion regime (NDR) was not even reached (in contrast to fiber oscillators) [13]. These high peak powers are combined with high average power in the range of few hundreds of watts. Moreover, carrier envelope phase (CEP) stabilization of a thin-disk oscillator was performed recently. Efficient external spectral broadening and compression resulted in 10 fs pulse duration and 10 W average power[14]. Such unique parameters of femtosecond thin-disk oscillators open doors to new exciting applications in research and industry.

2. KERR-LENS MODE-LOCKED THIN-DISK OSCILLATOR

The first SESAM mode-locked thin-disk oscillator was demonstrated in 2000 [15] and the first KLM thin-disk oscillator in 2011[11]. Despite of this “late” realization the progress in the development of KLM oscillators is incredibly fast. The first KLM thin-disk oscillator was demonstrated at 4 MW peak power and considerably shorter pulses as compared to SESAM mode-locked oscillators. Recent experiments performed in our lab demonstrate power scaling up to 30 MW [16]. Another group from Japan reported on about 50 MW (almost 1GW intra-cavity peak power) [17].

2.1 Cavity design

In order to make the analysis brief we refer to the cavity design of the Ti:Sa oscillator and numerous experimental and theoretical works published in the context of that development [18-22]. Here, we emphasis the main difference in the cavity design between the standard Ti:Sa oscillator and the thin-disk KLM oscillator. These main differences are: a) spatial separation of the Kerr medium from the gain medium, b) cavity design (convex-concave) leading to large spot sizes over all elements in the cavity. These differences are schematically illustrated in Fig. 1. The point a) makes it possible to change the nonlinearity in the Kerr medium by varying the thickness and medium type (in other words the nonlinear refractive index n_2). In contrast to the situation in Fig. 1a this procedure does not influence the absorption in

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the gain medium or oscillator efficiency. Additionally an increase of the mode size in the Kerr medium is possible by exchanging mirrors R1 and R2. Point b) helps to reduce constraints on the damage threshold of the intra-cavity optics and to realize a compact oscillator without the necessity for a longer cavity.

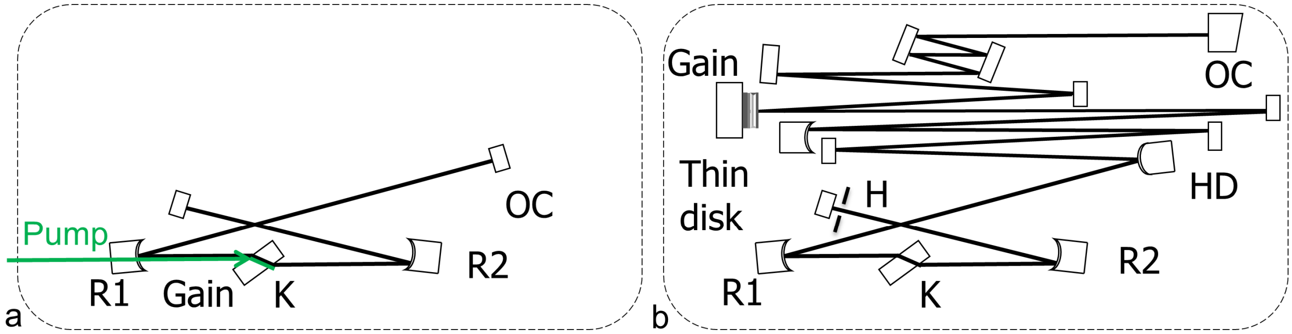

Figure 1. Rough graphical representation of the main differences between standard Ti:Sa X shape cavity (left) and the resonator of a KLM thin-disk oscillator (right). R1,R2 concave mirrors; K, Kerr medium; HD, high dispersive mirror; H, hard aperture; OC, output coupler. The cavity configuration is from [16]

2.2 Hard and soft aperture optimization

It is important to understand that hard and soft apertures KLM are generally not independent. The mode size at the position of the hard aperture depends on the mode size at the position of the soft aperture (gain). This coupling may result in much more complex saturation characteristics of the self-amplitude (SAM) coefficient of KLM. It is possible to suppress this coupling to some extent by choosing the resonator configuration in a way that the power dependent mode change in the gain medium is less pronounced than at the position of the hard aperture. Indeed, it is more beneficial to maximize both soft and hard aperture effects to obtain highest modulation depth. Experimental optimization of the hard aperture is simple and implies checking the influence of different aperture sizes on the KLM start-up, pulse duration and optical-to-optical efficiency. The aperture H diameter in Fig.1b is 4 mm and was optimized this way.

2.3 Advantages of the KLM technique.

A detailed analysis of the experimental results obtained for nearly the same cavity configuration with two different mode-locking techniques is presented in [23] and summarized in Table 1. A practical advantage of the KLM technique, especially in the development phase, is the ability to tune different parameters governing soliton mode-locking by simple manipulation of the cavity length, Brewster plate (Kerr medium) and hard aperture (drilled metal plate).

Table 1. Summary on disadvantages and advantages of two different mode-locking techniques.

SESAM	KLM
• non-saturable and saturable losses • two photon absorption • damage and degradation • reproducibility • finite relaxation time (~1 ps) • rather small modulation depth • high price	• emission-bandwidth limited pulses • no “real” losses • no degradation • no damaging • wavelength independent • low price
• easy to implement in a cavity	• laser operates close to the stability edge

3. ENERGY SCALING CONCEPT

3.1 Average power scaling

The main advantage of the thin-disk concept is power scalability [24]. It relies on an increase of the mode area in the gain medium proportionally to an increase of the pump power. This geometry is proven to provide high average powers and recently resulted in the nearly TEM_{00} operation at 1 kW level [25].

3.2 Experimental results

The main idea behind the energy scaling of KLM oscillator is a mode size increase in the Kerr medium. The onset of instabilities (like Q-switching, multiple pulses, CW breakthrough) is caused by the excessive nonlinearity arising when the peak power in the oscillator reaches some threshold value P_{max}. An increase of the mode size in the Kerr medium situates the onset of the excessive nonlinearity at higher intra-cavity values of P_{max}. This simple approach has been recently demonstrated experimentally in our group. Additionally to the increase of the mode diameter in the Kerr medium up to ≈120 µm, the group delay dispersion (GDD) was increased up to -48000 fs^2 and the number of passes through the disk was doubled. These measures resulted in 230 W average output power, 330 fs pulse duration and 11.5 µJ pulse energy which correspond to 30 MW peak power.

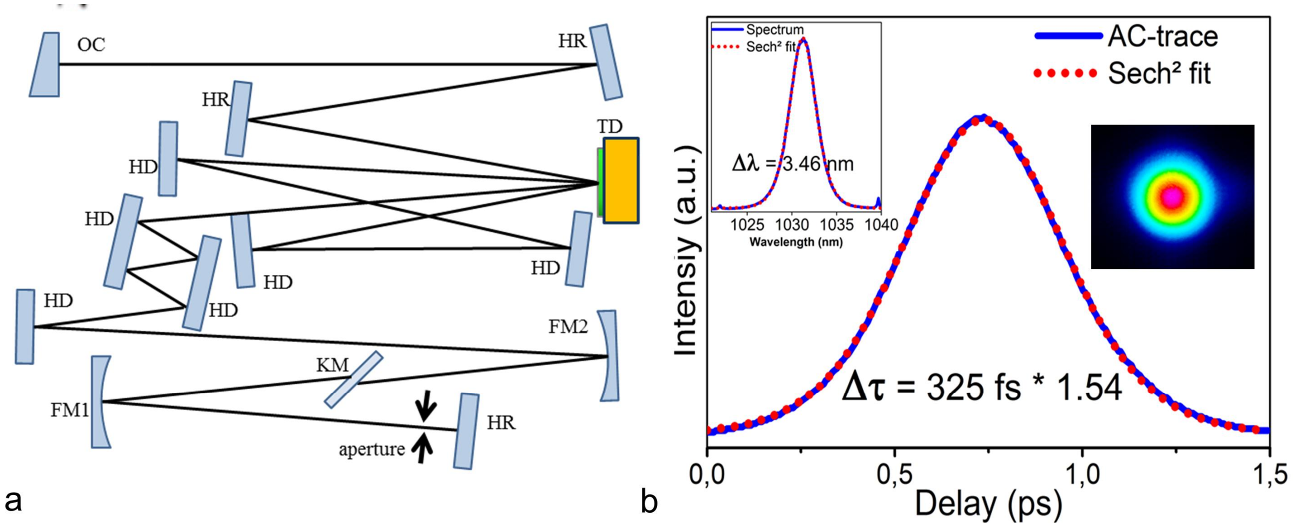

Figure 2. Cavity configuration (not to scale): OC: output coupler with 20% transmission, TD: Yb:YAG thin-disk, HD: high dispersive mirrors with ~ -3000 fs² per bounce, FM1,FM2: focusing mirrors with f=450 mm, KM: 1 mm thick sapphire-plate, HR: high reflectivity mirrors. b) Autocorrelation-trace, spectrum and corresponding beam-profile. The picture is taken from [16].

3.3 Main limitations

The theoretical limitations of the maximal achievable pulse energy from mode-locked oscillators are definitely not yet reached. The main limitations are originating from the experimental and technical side. These limitations can be summarized as: a) thermal effects in the intra-cavity optics, especially dispersive mirrors, b) thermal effects in the thin-disk gain medium, c) high sensitivity to the thermal effects at the stability edge, d) rather moderate modulation depth (5%) of the current configuration of the KLM resonator, c) nonlinearity of air for peak powers exceeding 300 MW

3.4 Possible industrial use

Industrial applications require incredible long term stability and reproducibility. This, in turn, requires serious engineering efforts to be done for KLM oscillators. Among these engineering efforts crucial ones are: a) thermal management of the laser housing and all optics and opto-mechnical parts, b) robust and mechanically stable housing, c) prevention of air flow inside the oscillator cavity, d) ultra-stable opto-mechanics.

4. FUTURE PROSPECTS

Based on the simple geometrical scaling concept of the KLM thin-disk oscillator and its intrinsically stable operation, CEP stabilized oscillators with average power levels of >300 W and peak powers >300 MW come into reach. Implementation of spectral broadening and compression will result in few-cycle pulses with an order of magnitude increased peak power (3 GW). These unique parameters will strongly expand the range of applications for these oscillators and turn many now unfeasible experiments into reality.

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