KERR LENS MODE-LOCKED THIN DISK OSCILATOR DEVELOPMENT AT HILASE

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Kerr lens mode locking (KLM) is an efficient way, how to generate ultrashort laser pulses. Employment of the KLM in thin disk-based lasers allows for generation of high average power ultrashort pulses reaching megawatts of peak power without adoption of the chirped pulse amplification technique. We demonstrate a small KLM Yb:YAG thin disk laser generating 240 fs long pulses close to 21 MHz repetition rate, nearly diffraction-limited beam, and average power of several watts. Mode locking is achieved in a thin slab of undoped YAG material. Next scaling of the system to tens of watts in average power allows for development of a compact femtosecond laser for seeding of kW-class thin disk laser platform Perla, or direct industrial use.

KEYWORDS

Thin disk laser, mode locking, femtosecond laser, Yb:YAG, laser oscillator, Kerr lens, high power laser

1 INTRODUCTION

Kerr lens mode locking is an advanced method of pulsed laser operation. After being first observed in 1990 [Spence 1991], it has become a widely used approach for achieving ultrashort pulses down to several fs duration. In the beginning it was mostly used in bulk Ti:Sapphire resonators to achieve long-standing records of minimum laser pulse durations only surpassed by attosecond pulses created by high harmonic generation. It is a versatile technique used in all kinds of systems operating at different wavelengths from broadband emitting solid state lasers to extremely compact fiber lasers. Such lasers can be used in variety of applications including seeding of systems of complex laser amplifiers [Smrz 2017].

2 KERR LENS MODE LOCKING

Mode locking is a method of achieving ultra-short laser pulses by essentially making the conditions of light propagation inside a laser resonator unfavorable for continuous-wave (CW) operation and simultaneously simplifying those conditions for pulses travelling inside the resonator. Thus, the individual resonator longitudinal modes are forced to enter a state where their phases become locked with each other, hence the name mode locking. After phasing of longitudinal modes a periodical pulse train is observed at the output of the oscillator [Haus 2000]. Each mode-locked oscillator consists of a mode locking mechanism that enforces this pulsed behavior inside the resonator and shortens the pulse duration by its nonlinear response upon each cavity roundtrip, and of a gain medium, which amplifies the pulse and increases its duration, mainly by dispersion effects. There are several ways to introduce the aforementioned conditions to a resonator. The first and most common method is to use a saturable absorber. This optical element features variable absorption of light that is dependent on the incoming light intensity. The higher the intensity, the lower the absorption. As such, high-intensity pulses are subjected to smaller losses inside the resonator and are further amplified in the gain medium, whereas low-intensity pulses or CW light is fully absorbed in the saturable absorber. Currently, mostly utilized type of saturable absorber are semiconductor saturable absorber mirrors (SESAMs).

Another method is to use Kerr nonlinearity of an optical material to induce a lensing effect by passing high intensity light propagating through this medium. This intensity-dependent lens then changes the mode size inside the resonator. If an aperture is placed in the resonator in an optimal location, the mode size for CW light or low-intensity light will be too large to allow lossless transit through the aperture. However, high-intensity pulses pass through the aperture with negligible losses due to the Kerr lens induced mode size change. The high-intensity pulses are then further amplified in the gain medium while the low-intensity pulses are attenuated at the aperture, and amplification at the gain medium cannot overcome these losses. This is called hard aperture mode locking, as opposed to soft aperture mode locking, where the mode size difference between high-intensity and low-intensity pulses causes the low-intensity resonator mode to be larger than the pumped area of the gain medium. Therefore, low intensity pulses cannot be sufficiently amplified to overcome the resonator losses. In addition to the Kerr lens effect, self-phase modulation is also induced inside the nonlinear medium. This effect introduces a substantial chirp inside the resonator which then must be compensated with other optical elements inside the cavity but helps to shorten the pulses. Dispersion compensation is necessary in some way in nearly all mode locked oscillators designed to produce fs pulses, as the dispersion present in the gain medium and other optical elements inside the cavity prevents generation of the shortest pulses and cannot be ignored.

Kerr lens mode locking has a significant advantage over other kinds of mode locking in a fact that the self-phase modulation induced inside the nonlinear Kerr medium broadens the spectrum of the pulse. In addition, the combination of a Kerr lens and aperture has a much faster response time in comparison to SESAMs. This makes achieving shorter pulses easier and also broadens the possibilities for further compression after the pulse leaves the oscillator. Because of these factors, SESAMs are limited in terms of achievable pulse durations and pulse energies when trying to produce pulse durations well below 1 ps, whereas Kerr lens mode-locked (KLM) oscillators can produce pulses nearly gain-bandwidth-limited pulses at high average power. Another positive of KLM is that SESAMs tend to have much lower damage threshold which can lead to frequent laser-induced damages during the mode locking. Even though this fact can be circumvented by careful cavity design, it needs to be considered when utilizing SESAMs to achieve mode locking.

Despite these advantages, KLM is not always the best option. Resonator design is much more complicated when considering the requirements of KLM. In order for the Kerr lens to have a considerable impact on mode size in the resonator, the resonator must be designed close to its stability edge. In fact, a KLM approach exists that omits placing an aperture inside the resonator and, instead, the resonator is operated outside of the stability range using the Kerr Lens to make the resonator stable only for pulsed operation of the laser [Yefet 2013]. Operation near the stability edge can negatively impact the overall stability of the laser output, as the laser is more liable to be disrupted by passive airflow through the resonator or background vibrations. Because the optical power of the Kerr lens is proportional to the intensity of the pulse, it can also be quite challenging to start the mode locking process inside the resonator and some designs resort to placing a SESAM inside the KLM oscillator cavity to achieve reliable self-starting. While self-starting oscillators relying purely on KLM exist, their construction is not trivial, especially if one wishes to avoid multi-pulsing behavior and output energy stability is crucial.

2.1 Thin disk oscillators

In order to utilize the benefits of Kerr lens mode locking, it is important to consider the gain medium and its architecture. As with all mode locked lasers, a gain medium with a broadband emission spectrum is necessary to achieve ultra-short pulses. When designing a laser to obtain fs pulses, the nonlinearity of this medium must also be considered and should ideally be minimal, unless it is intended for the gain medium to also be the Kerr lens medium. On top of that, it is beneficial to select a gain medium architecture so that the cavity design for KLM is not limited by the architecture of the gain medium. Thin disks are well suited for this purpose. Using Yb:YAG as the gain medium, thin-disk oscillators are capable of generating pulses under 200 fs in duration at high average powers and excellent beam quality, thanks to the thin-disk design that suppresses thermal lensing in the gain medium along with self-phase modulation. Thin-disk oscillators with average powers well beyond 100 W and excellent beam quality have been demonstrated [Brons 2016], an achievement either extremely difficult if not impossible with other types of oscillators. Thin disk technology is in general well suited to high average power applications.

Thin disk lasers are also energy-scalable. Scaling is performed by proportionally increasing the pump power on the disk while increasing the pump area on the thin disk to preserve ideal pump intensity. This has to be accompanied by changing the cavity mode size on the disk, which means this procedure does have its limitations, however these limits go far beyond what most other types of gain media are able to accomplish in terms of scaling, up to kW-level average power systems. . While Yb:YAG is currently the most common gain medium used in thin-disk oscillators, it is possible to use other types of gain media such as Ho:YAG [Zhang 2017], $Yb:Lu_2O_3$ [Paradis 2017] and $Yb:Y_2O_3$ [Tokurakawa 2012].

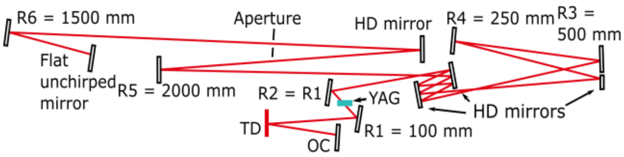

Figure 1. Optical scheme of the KLM oscillator system developed for the pilot test at HiLASE (HD – dispersive mirrors, R1-R6 - concave spherical mirrors with various radii of curvature (ROC), TD - thin disk laser head, YAG – Kerr medium, OC - output coupler).

Thin disk KLM oscillators usually produce pulses at high repetition rates in the range of 1 -100 MHz. This is given by their cavity length, and means that the single pulse energy of these systems is usually lower than of a thin disk regenerative amplifier, which are commonly used to achieve high pulse energy. Although it is possible to achieve fs pulses with Yb:YAG regenerative amplifiers by intracavity-induced self-phase modulation, such an endeavor is very challenging due to the increased requirements for careful cavity design and pulse compression [Neuhaus 2017]. The main allure of KLM oscillators over amplifier systems is besides their high average power the compactness and single-box design of oscillators, requiring much less space than advanced amplifier systems with regenerative amplifiers.

2.2 Application of Kerr Lens Mode locked oscillators

One of the most direct applications of fs pulses is, for example, in laser ablation of materials. Laser ablation in general relies on irradiating a sample with high fluence to effectively evaporate a portion of a sample while keeping interaction time short for thermal diffusivity to transfer a substantial amount of heat to the surrounding zone. In short it can be described as non-thermal vaporization. Despite the fact that ablation of metals is most often performed using ps or ns laser pulses to maximize overall ablation rate, fs pulses offer further reduction of the heat affected zone. This makes fs pulses ideal for precise micromachining. Another factor to consider is the fact that most materials are capable of incubation of energy for laser ablation, which means that irradiating the target by multiple pulses in rapid succession reduces fluence threshold for ablation [Emmert 2010]. It is therefore less challenging to design a laser capable of ablation in terms of pure energy and allows for beam quality and pulse width to be the main focus of laser design. In addition, several detrimental effects that

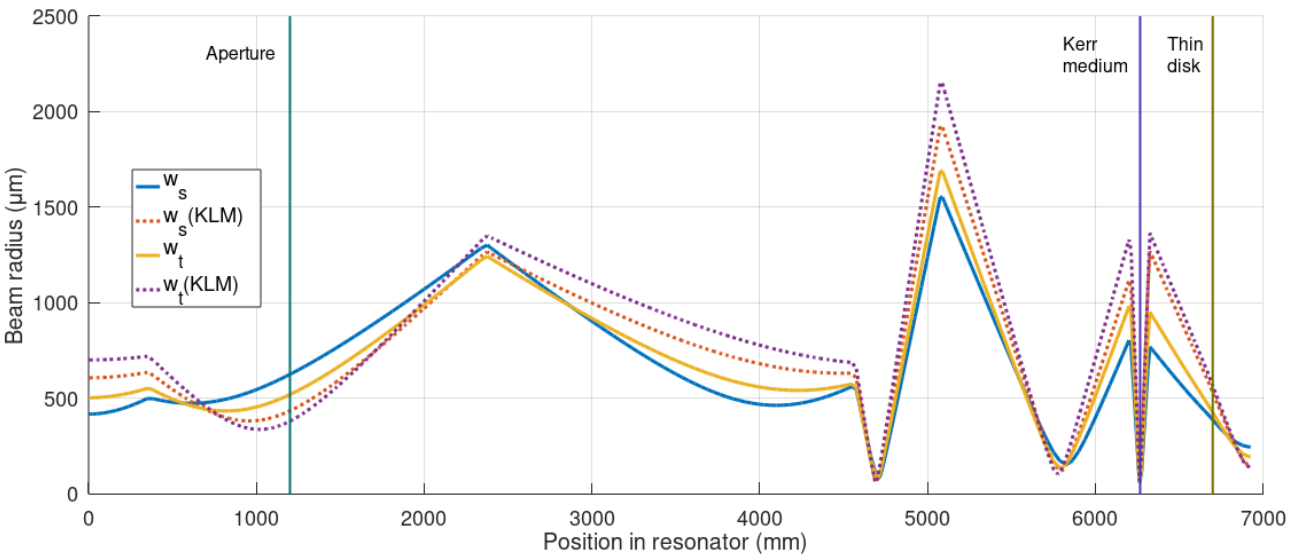

Figure 2. Simulated caustic of the mode inside the KLM oscillator's cavity in pulsed (dotted), and CW (solid) operation. Subscript *s* denotes the caustic in sagittal direction, *t* in tangential direction.

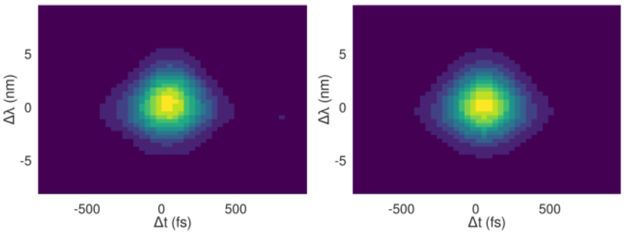

Figure 3. SHG FROG traces of the output pulse. Measured (left) and retrieved (right).

accompany laser ablation of metals in particular are suppressed when ablating at very high pulse repetition rates [Kerse 2016]. This makes thin disk mode locked oscillators ideal candidates for this application, as they are capable of delivering fs pulses at MHz repetition rates and reasonably high pulse energies.

The situation is much different when considering dielectrics as the target material. Due to the larger band gap, laser ablation is either possible with the use of UV light, or at very high intensities via nonlinear phenomena. These phenomena include multi-phonon absorption, tunneling ionization and potentially even over-the-barrier ionization. The latter two effects rely on an electric field strong enough to substantially perturb the Coulomb potential to allow excitation of an electron from valence band to the conductive band. As such, fs pulses are essential to achieve good quality laser ablation of dielectrics with near infrared light. However, one aspect of dielectric ablation that simplifies the process is the fact the thermal conductivity of dielectrics tends to be low, which translates to a very small heat affected zone, but can also increases the risk of fragmentation, depending on the ablated material [Balling 2013].

Another potential application of thin disk mode locked oscillators in material processing is in the fabrication of laser induced periodic surface structures (LIPSS). These structures are a result of interaction between solid material and high intensity polarized light. The patterns are confined to the surface layer of a material and the spatial period of these structures is usually hundreds of nm, however structures with sub-100 nm period have been demonstrated [Bonse 2012]. LIPSS found application in selective coloring of materials, for optical data storage, marking, or security features. LIPSS were also used to improve wettability of a surface to form hydrophobic surfaces [Bonse 2017].

3 CURRENT DEVELOPMENT AT HILASE

Kerr lens mode-locked oscillators are currently being developed at HiLASE, using internally developed new generation of components and housing for the thin disk. Our current system consists of a diode-pumped thin-disk oscillator with a 7 m long standing-wave laser cavity. A block scheme of the oscillator can be found in Fig.1. A graph of the simulated beam radius inside he cavity including the estimated beam radius for pulses when KLM is established is presented in Fig. 2. The thin disk used in the setup was a soldered Yb:YAG with 7.2% doping, 220 µm thickness, and a radius of curvature (ROC) of 4200 mm. The aperture is placed approximately at position 1200 mm in the graph shown in Fig. 2. Here the aperture has maximal impact on the mode, which gets substantially smaller during KLM.

The pumped area on the disk was 1.245 mm in diameter and maximum pump power used 58.7 W, indicating a maximum pump intensity on the disk 4.82 kW/cm^2. This is close to the optimal disk saturation. Next significant increase in pump power would require a cavity redesigning to accommodate a larger mode on the thin disk. The Kerr medium placed inside the cavity is a 2 mm slab of undoped YAG, inserted into the cavity at a Brewster's angle to minimize reflection losses at the cost of slight astigmatism of the output beam.

The oscillator is capable of delivering 240 fs long pulses when assuming a sech^2 shape at repetition rate of 21 MHz. The pulse duration measured with FROG (Fig.3) was 255 fs. In order to match the positive GDD of the self-phase modulation, dispersive mirrors of a total GDD of –16600 fs^2 are used. The output average power of the laser is 2.04 W, which corresponds to a peak power of 5.92 MW, and 96.9 nJ pulse energy when using an output coupler with a transmissivity of 6%. The oscillator's cavity is also capable of CW operation at the cost of output average power reduction. Fig. 4 shows the comparison of the typical output spectra of the laser in these two operation regimes.

The spectral bandwidth (FWHM) of the output pulse was 4.69 nm when measured with a spectrometer and 5.9 nm when using FROG. The discrepancy is caused by spectral sampling of the FROG measurement. The mode locking is currently not self-starting, it can be started by tapping a mirror post of one of the end cavity mirrors.

The output beam was nearly diffraction limited. The output beam profile is shown in Fig. 5. The beam quality changes slightly when operating in CW mode, which is given by different stability conditions.

3.1 *Further development plans*

Future development of this system is improving all possible aspects of the system. Of all these aspects, an increase of the output pulse energy is the main focus of development. Several options for achieving this, including raising of the pump power and changing the cavity design to utilize multi-pass thin-disk configuration in the cavity, have been proposed [Brons 2016].

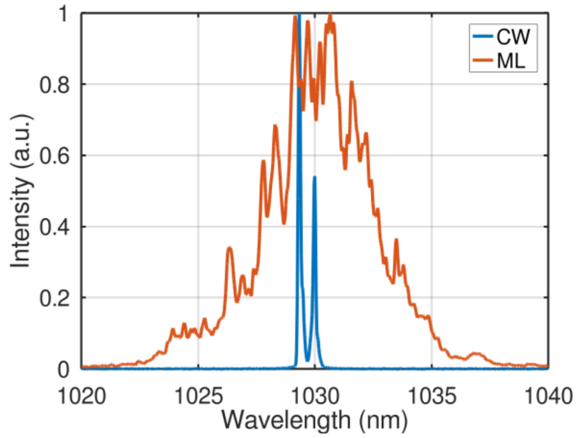

Figure 4. Comparison of output spectrum of the laser in two modes of operation, continual wave (CW, blue) or mode-locked (ML, red).

Redesigning the cavity to include this feature would bring the laser closer to saturation. The oscillator is currently built on an optical table, but without proper shielding it is prone to airflow-induced disruptions. Other aspects we are planning to improve are beam quality and overall compactness of the oscillator.
In order to improve long term stability of the system, airflow through the resonator should be suppressed as much as possible. It cannot be fully eliminated without operating the cavity in a special housing or under lower pressure, if air

breakdown by high intensity needs to be prevented as well. On the contrary, this could increase the heat load of some components.

A new cavity design could also hopefully achieve an increase in the effect of Kerr lens on the mode size in the resonator, making starting of the KLM easier and output pulse energy and stability higher.

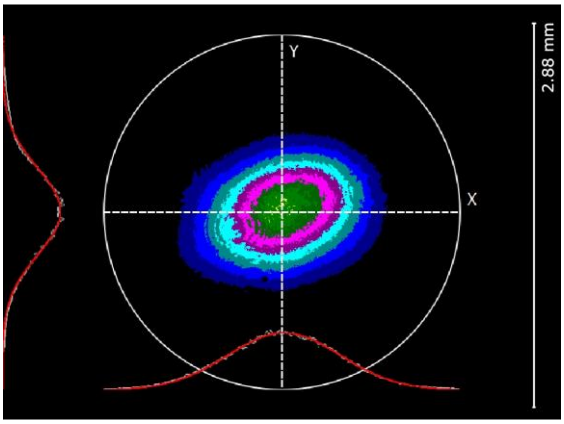

Figure 5. Output beam profile of the thin-disk oscillator generating pulses in mode-locked regime.

4 CONCLUSION

Hilase started to develop a thin-disk-based femtosecond oscillators targeting at pulse energy reaching of several µJ. Such lasers are useful for stress-free material ablation, creation of periodic surface structures, and generally material processing. Pilot experiment using in-house technology was done and results generated by this KLM oscillator are presented, along with a brief summary of mode locking mechanisms and application examples. We were able to generate stable pulse train of 0.1 µJ pulse with pulse duration <250 fs by Kerr lens mode locking.

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