Powerful 67 fs Kerr-lens mode-locked prismless Yb:KGW oscillator

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Abstract: We report on the generation of 67 fs pulses from a diode pumped Kerr-lens mode-locked Yb:KGW bulk laser. The average output power reached 3 W, corresponding to >38 nJ of pulse energy and >570 kW of peak power. The mode locking was initiated by a semiconductor saturable absorber. To the best of our knowledge, this is the highest average output power produced to date from Yb-ion based bulk lasers with such a short pulse duration.

OCIS codes: (140.3580) Lasers, solid-state; (140.3480) Lasers, diode-pumped; (140.7090) Ultrafast lasers; (140.4050) Mode-locked lasers.

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1. Introduction

Over the past decade, Yb-ion doped gain media have become the material of choice for reliable generation of ultrashort pulses. This can be attributed to their excellent lasing properties, broad emission bandwidths and compatibility with diode pumping. Operation at high average power (>1 W) with sub-100 fs pulses, however, still remains quite challenging. Such a mode locking regime is accompanied by an increased influence of nonlinear effects, which necessitates careful management of the intracavity dispersion. At the same time, uncompromised performance of the mode locking mechanism is needed to sustain ultrashort pulse generation effectively and to alleviate increased pulse instabilities. This is a nontrivial task for semiconductor saturable absorber based pulse generation and as a result higher output power usually comes at the cost of longer pulse duration. For example, Yb:KGW lasers have produced 10 W of output power with 433 fs pulses [1] and 126 mW with 100 fs pulses [2]. Similarly, a laser based on a sister material, Yb:KYW, generated 14.6 W and 450 fs pulses [3] while 65 fs pulses were produced at 22 mW [4]. The same trend is found in thin-disk oscillators [5]. As an alternative to semiconductor saturable absorbers, Kerr-lens mode locking (KLM) is a well-established technique that produces ultrashort pulses and is routinely used for the generation of sub-10 fs pulses from Ti:sapphire oscillators [6]. Unlike semiconductor absorbers, KLM exhibits a purely electronic response, thus acting as a fast saturable absorber. This is beneficial for enhanced pulse shortening and increased mode locking stability against the continuous wave background radiation present in a cavity. Therefore, the fast saturable absorber-like action of KLM is attractive for the generation of intense ultrashort pulses.

In this work, we report on a powerful Kerr-lens mode-locked Yb:KGW bulk oscillator. Our motivation for using an Yb:KGW laser crystal comes from the fact that it has one of the highest emission cross-sections (2.8×10^{-20} cm^2), fairly broad amplification bandwidth (~20 nm), and relatively high thermal conductivity (~3.3 W/m/K) [7]. High average output power in the continuous wave and mode-locked regimes were demonstrated [1], and the shortest reported pulses [2] were not limited by the available gain bandwidth. In addition, the crystal is characterized by a high value of the nonlinear index of refraction [8] and absence of two-photon absorption at 1 μm wavelength [9], all of which contributes to efficient Kerr lensing both at low and high laser light intensities. Moreover, this crystal is commercially available.

2. Experimental setup

The Yb:KGW crystal (Eksma) used in the experiment had a slab geometry which was 5 mm long (along the beam propagation direction) and 1.2 mm thick. The crystal with 1.5 at.% doping level was antireflection coated and cut along the N_g-axis. When compared to the

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commonly used 5 at.% doped crystals, the lower doping level is more adequate for generating shorter pulses since a higher level of population inversion can be reached under the same pump conditions, leading to spectral broadening of the gain [10]. The crystal was pumped at normal incidence with a maximum of 30 W of pump radiation delivered from a fiber-coupled diode laser (100 µm core diameter, 0.22 NA). The pump beam was reimaged into the crystal by a 1:3 imaging module consisting of two achromatic doublets, forming a beam waist of 300 µm at the center of the crystal. To optimize the spatial matching between the pump and cavity modes, the Z-fold cavity depicted in Fig. 1 was designed. The crystal was placed between two highly reflective (HR) concave mirrors R1 and R2 (radii of curvature r = 300 mm), resulting in a cavity mode size of around 300 µm inside the crystal. The collimated cavity mode in the long arm was further focused by a third HR concave mirror R3 (r = 500 mm) onto the output coupler. The distance between the output coupler and R3 could be precisely adjusted through a micrometer driven translation stage. This allowed for continuous control of the cavity mode size inside the crystal.

The initial "cold" cavity design was optimized for KLM performance by treating the Kerr effect as an additional positive intracavity lens [8] with variable focal length. All HR cavity mirrors were designed to exhibit low group velocity dispersion at the laser wavelength (Laseroptik GmbH). Two Gires-Tournois interferometer (GTI) mirrors (Layertec GmbH) were inserted into the long arm, providing a negative round-trip dispersion of 3200 fs^2 to balance the positive dispersion of about 1700 fs^2 introduced by the crystal and the additional chirp due to self-phase modulation.

The short arm of the cavity was terminated with a semiconductor saturable absorber mirror (SESAM, Batop GmbH) which was designed for 1040 nm wavelength with a modulation depth of 2%. The SESAM was used to initiate KLM operation. The spot size on the SESAM was designed to be about 500 µm in diameter in order to tolerate the high intracavity power. To achieve high output power an output coupler with higher transmittance should be used. On the other hand, lower transmittance is desirable for obtaining shorter pulses in the mode locking regime because of the lower laser gain [10]. Considering these contradictory requirements, an output coupler with 10% transmittance at the lasing wavelength was chosen. The cavity length resulted in a repetition rate of 77 MHz in single pulse mode-locked operation.

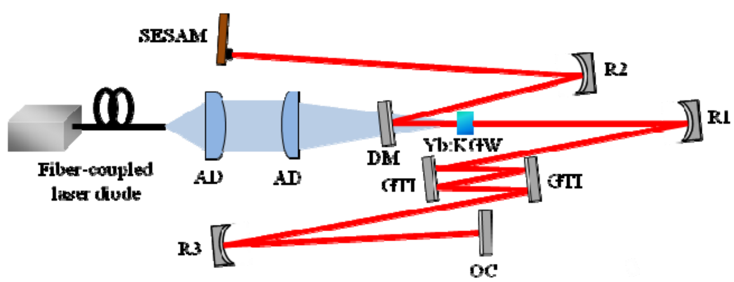

Fig. 1. Experimental setup of Kerr-lens mode-locked Yb:KGW oscillator. AD: achromatic doublets; DM, dichroic mirror; GTI: Gires-Tournois interferometer; R1, R2, R3: concave mirrors; OC: output coupler.

3. Results and discussion

In preliminary experiments the cavity was optimized for operation in the continuous wave (CW) regime by using an HR mirror in the short cavity arm instead of the SESAM. The CW output power reached 6 W with 30 W of pump power incident on the crystal. The laser radiation was polarized parallel to the N_m-axis. The pump power absorption under non-lasing conditions was measured to be 50-60%, depending on the power level. A pump-power-dependent thermal lens, along with the Kerr lens, is always present as a parasitic factor when the laser operates in the pulsed regime, which affects the cavity's stability, beam astigmatism

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and starting of the KLM. The thermal lens strength was estimated in the CW regime by measuring the variation of the beam size away from the output coupler and then finding the lens strength using the ABCD matrix method. With 30 W of pump power incident on the crystal (~18 W absorbed), the thermal lens strength was determined to be about 10 diopters. Taking the thermal lensing into account, the cavity was designed to be operated close to the center of the stability region and the cavity mode was well matched with the pump mode inside the crystal. The output beam had an almost circular spatial profile (see Fig. 4).

As the HR mirror was replaced by the SESAM, a Q-switched mode locking (QML) regime with large fluctuations in the envelope amplitude was instantly observed. The average power dropped to 4 W because of the large non-saturable loss of ~2% of the SESAM. The strong tendency towards QML instability was caused by the large spot size on the SESAM, leading to a low fluence of ~200 μJ/cm^2, which is less than 3 times its saturation fluence (~70 μJ/cm^2). In this case, the QML regime was purely initiated and governed by the SESAM. The spectral width of the QML pulses was ~5 nm. As the cavity length was adjusted so that the cavity mode size became larger than the pump spot, a soft aperturing via the Kerr lensing effect was effectively introduced, leading to an increased discrimination between the CW/QML and mode-locked regimes. During this procedure, KLM gradually took over from SESAM mode locking (ML) and became the dominant ML mechanism. This can be seen in Fig. 2 which shows different ML regimes during the optimization of the cavity length at maximum pump power of 30 W: QML was followed by a multipulse operation, which eventually led to a stable ML with a single pulse inside the cavity.

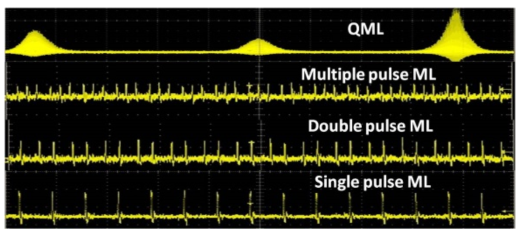

Fig. 2. Shape of the pulse trains in different mode locking regimes.

Initially, as the output coupler was translated several millimeters closer to R3, the QML instability was suppressed and gave way to multiple-pulse ML. According to soliton theory [11], this regime is caused by incomplete discrimination between ML and amplification of the continuum. In this regime the average output power decreased to 3.6 W and the spectrum was broadened to ~9 nm. With further increase of the cavity mode size, the double-pulsing regime was reached, indicating better suppression of the multiple-pulse instabilities by the Kerr lensing. In this domain, the emission spectrum was measured to be ~11 nm wide and the average output power further decreased to 3.5 W. As the cavity was completely optimized (at ~20 mm away from the starting point), the multiple-pulse instability was fully suppressed, resulting in the oscillation of a single pulse inside the cavity. As a result a broad spectrum with a bandwidth of 16.8 nm (FWHM) centered at 1032 nm was obtained (Fig. 3). At this point the SESAM was weakly saturated with a fluence of only ~170 μJ/cm^2, indicating that KLM was the dominant ML mechanism. A similar transition from multiple-pulse SESAM-based ML to single-pulse KLM operation was also observed in Yb:Sc_2O_3/Y_2O_3 laser [12]. It also should be noted that pure KLM without the SESAM was not achieved in this experiment.

The autocorrelation trace of the pulses was acquired by using a commercial long range (200 ps) autocorrelator (Femtochrome, FR-103XL) and is shown in Fig. 3. The longer time ranges were monitored with a fast photodiode and an oscilloscope with combined resolution of ~100 ps. Assuming a *sech*^{2} temporal shape, the typical pulse duration at the output of the laser was determined to be 68 fs. The time-bandwidth product was calculated to be 0.32, indicating transform-limited operation. The average output power was 3 W, resulting in a pulse energy of more than 38 nJ and a peak power of more than 570 kW. This is, to the best our knowledge, the highest average output power achieved with such a short pulse duration from an Yb-ion based bulk laser oscillator. The optical-to-optical efficiency with respect to the incident pump power was 10%. The shortest measured pulse duration was 67 fs at the same output power level.

To illustrate the effect of Kerr lensing on pulse duration, an additional experiment was performed where stable SESAM-based ML was achieved in a cavity that was not optimized for KLM. The output power was similar. The spectral bandwidth of the mode-locked pulses, however, was only to 5-6 nm, which is consistent with our previous results [13].

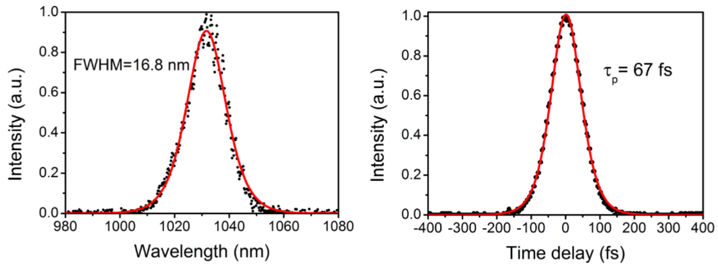

Fig. 3. Measured spectrum and autocorrelation trace of the pulses with fits assuming a *sech*^{2} profile. The pulse duration was determined to be 67 fs.

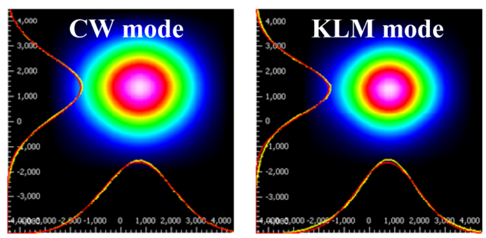

Fig. 4. Beam profiles of the CW and mode-locked output beams.

In Fig. 4 the output beam intensity profiles in the CW and KLM regimes are displayed. The beam shape in the KLM regime had an almost circular profile, but with a smaller diameter than the output beam in the CW regime due to self-focusing of the cavity mode inside the crystal. The beam quality factor M^2 was measured to be close to 1.1. In contrast to traditional KLM lasers, which usually operate at the edge of the stability region in order to maximize self-amplitude modulation, the laser described in this article operated close to the center of the stability region. In this case the self-amplitude modulation responsible for the initiation of the ML process was effectively provided by the SESAM. Unlike KLM cavities with tightly focused laser beams inside the crystal, the described cavity had a much broader stability range and lower sensitivity to optical misalignment, leading to much easier alignment and better performance on a daily basis.

The peak intensity of the oscillating pulse inside the cavity was calculated to be ~0.8 GW/cm^2. Such high intensity may cause additional nonlinear loss in the Yb:KGW crystal because of its large coefficient of stimulated Raman scattering. During the experiments, however, no stimulated Raman scattering was observed. This can be explained by the transient nature of the process, which leads to an increased threshold [14].

As a comparison, the performance of previously reported Yb-ion bulk lasers is summarized in Fig. 5 [4, 12, 15–22]. Very short pulses with durations of <70 fs have been generated by many Yb-doped materials, either with a SESAM or Kerr-lens mode locking. In most cases, however, the average output power was limited to tens or hundreds of mW. As a notable exception, in Tokurakawa's work KLM proved its potential in power scaling of ultrashort pulse generation, demonstrating 66 fs pulses at an average output power of 1.5 W from a dual-gain medium (Yb:Sc_2O_3 and Yb:Y_2O_3) [12]. In contrast, in this work only a single gain medium was used and the average output power was improved by a factor of two

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with similar pulse duration. In another recent KLM experiment, 2.3 W were produced from an $Yb:CaF_2$ laser with 75 fs pulses and extracavity compression down to 68 fs. This laser, however, was not directly diode-pumped and required a diffraction limited pump beam [22].

The output power of our setup was limited by the available pump power and the non-saturable losses of the SESAM. Power scaling beyond 10 W may be possible with Kerr-lens mode-locked thin-disk oscillators, where 17 W of average output power with 200 fs pulse duration was reported using an Yb:YAG crystal [23]. Alternatively, generation of even shorter powerful pulses may require the use of a broadband gain medium such as Yb:CALGO, which was recently shown to produce 80 fs pulses at 8 W output power in a bulk configuration [24], and 62 fs pulses at 5.1 W output power in a thin-disk configuration [25].

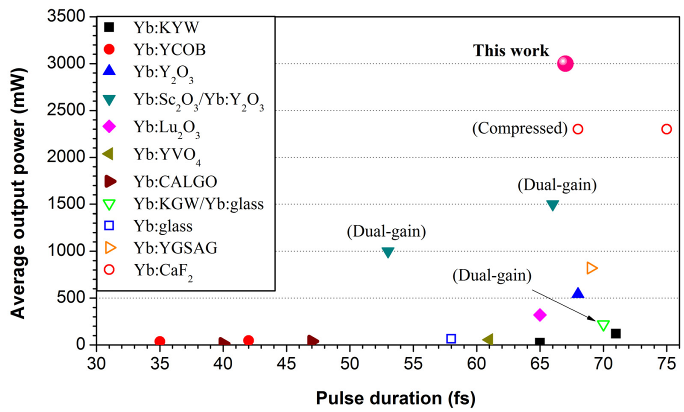

Fig. 5. Average output power of mode-locked Yb-ion bulk lasers versus pulse duration.

4. Conclusion

In conclusion, we have demonstrated a high power SESAM-assisted Kerr-lens mode-locked Yb:KGW laser. With optimized dispersion compensation, the laser delivered pulses with 67 fs duration at a repetition rate of 77 MHz. The average output power reached 3 W, which to the best of our knowledge makes it the most powerful Yb-ion bulk laser oscillator at this level of pulse duration.

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