Efficient femtosecond high power $Yb:Lu_2O_3$ thin disk laser

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Abstract: We demonstrate the first passively mode-locked thin disk laser based on $Yb:Lu_2O_3$. The laser generates 370-fs pulses with 20.5 W of average power in a diffraction-limited beam ($M^2 < 1.1$). The nearly transform-limited pulses have a spectral bandwidth of 3.4 nm centered near 1034 nm. With slightly longer pulses (523 fs) we obtained 24 W of average power at a pump power of 56 W, resulting in an optical-to-optical efficiency of 43%, which is higher than for any previously mode-locked thin disk laser.

OCIS codes: (140.3380) Laser materials; (140.3480) Lasers, diode-pumped; (140.3615) Lasers, ytterbium; (140.4050) Mode-locked lasers

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1. Introduction and motivation

High power lasers have attracted significant interest over the past few decades and are widely used in scientific and industrial applications today. Many of these applications benefit from the high peak powers that can be obtained from femtosecond pulses with pulse energies in the microjoule regime. The thin disk laser concept [1] has been successfully used in combination with a semiconductor saturable absorber mirror (SESAM) [2,3] for passive mode locking to directly generate such pulses. Without the need for additional external amplification, this concept has resulted in very robust and compact lasers, with which power scaling can be achieved by simultaneously increasing the mode size on the gain material and the absorber [4]. Average powers of up to 80 W [5,6] and pulse energies beyond the 10 μJ level [7] have been obtained using diode-pumped Yb:YAG thin disk lasers. Yb:YAG is easy to grow with high quality using the Czochralski method. Its excellent thermo-mechanical properties made it the de facto standard material in today's industrial thin disk laser sources, with multi-kilowatt output powers in continuous-wave (cw) operation. However, the narrow amplification bandwidth of Yb:YAG limits the obtainable pulse duration to ~700 fs in efficient high power mode-locked operation even though much shorter pulses have been obtained in the low power regime: 340 fs with an average output power of 170 mW [8] and 136 fs with 3.1 mW due to additional intracavity spectral filtering [9].

With an Yb:KYW thin disk laser we have obtained shorter pulses with a duration of 240 fs at 22 W of average output power [10], which again was longer than the ~100 fs at 100 mW [11]. Unfortunately, the Yb:KYW disks have the tendency to become astigmatic during the coating process due to the anisotropic nature of the material [12]. This makes operation with larger mode areas and therefore power scaling more difficult.

In this letter, we present the first passively mode-locked femtosecond thin disk laser based on Yb:Lu_2O_3. We obtain an optical-to-optical efficiency unprecedented in passively mode-locked thin disk lasers. The average output power of 24 W is limited only by the available pump power. In contrast to Yb:KYW, we do not expect any problems with further power scaling.

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2. Yb:Lu_2O_3 gain material

The sesquioxide materials are particularly attractive for the thin disk configuration because of their excellent thermo-mechanical properties. Undoped Sc_2O_3, Y_2O_3, and Lu_2O_3 all have a thermal conductivity superior to that of YAG [13]. Doping the materials with ytterbium ions leads to a drop in thermal conductivity, which remains highest for Lu_2O_3 due to the similar atomic weights of ytterbium and lutetium. The thermal conductivity of Yb-doped Lu_2O_3 is therefore still significantly higher than that of Yb:YAG. According to Ref. [13], at a doping level of 3 at.% the thermal conductivity of Yb:Lu_2O_3 is 11 W/(m·K) and that of Yb:YAG is 6.8 W/(m·K). Moreover, at equivalent Yb-densities, a lower disk thickness is required for Yb:Lu_2O_3 to obtain the same absorption as for Yb:YAG, which is beneficial for heat removal. This is due to the higher absorption cross section of Yb:Lu_2O_3 ($\sigma_{abs} = 3\cdot10^{-20}$ cm^2), which is pumped at its zero-phonon-line (ZL) wavelength (976 nm). In comparison, Yb:YAG has its absorption maximum ($\sigma_{abs} = 0.8\cdot10^{-20}$ cm^2) at 940 nm, where the absorption peak is much broader than at its ZL wavelength (969 nm). Thus the only trade-off is that the narrower absorption peak of Yb:Lu_2O_3 at 976 nm with a FWHM of only 2.1 nm leads to higher demands on the pump diodes.

In addition, Yb:Lu_2O_3 is attractive because of its broader amplification bandwidth compared to that of Yb:YAG. The material is therefore suitable for the generation of shorter pulses. Low power experiments with a bulk Yb:Lu_2O_3 crystal have resulted in 220-fs pulses at 266 mW of average power with an optical-to-optical efficiency of 15.5% using a titanium-sapphire laser for pumping [14]. With diode-pumping, a broad cw tunability with more than 10 W of average power over a tuning range of 90 nm has recently been demonstrated in the thin disk configuration [15].

However, the crystal growth of sesquioxide materials is challenging, due to the high melting temperatures above 2400°C. The high quality Yb:Lu_2O_3 used in our experiment was grown with the heat exchanger method (HEM) using a high-purity rhenium crucible and an optimized atmosphere. With this growth technique, polycrystalline boules of 40 mm in diameter were produced containing highly homogeneous monocrystalline regions with a volume of up to 5 cm^3. In cw operation, a remarkably high optical-to-optical efficiency of up to 72% and a slope efficiency of 80% has been achieved thanks to the significantly improved crystal quality obtained with this improved HEM [15]. The fabrication of ceramics is also being investigated as an alternative to the difficult crystal growth [16], however, Yb:Lu_2O_3 ceramics have not yet been used at high power levels in the thin disk configuration and similar efficiencies have so far not been obtained.

The Yb-doping concentration of our crystal is 2%, corresponding to an ion density of $5.8\cdot10^{20}$ cm^{-3}. The disk has a thickness of ≈250 µm and is coated on one side with a highly reflective coating for both pump and laser wavelength and soldered onto a water-cooled heat sink. The opposite side has an antireflective (AR) coating for the same wavelengths. The disk was polished with a wedge of ≈0.05° intended to eliminate effects that could arise from residual reflections of the AR coating. The crystal is pumped with a fiber-coupled 976-nm diode laser delivering a maximum power of 56 W with a spectral width of <2.5 nm. The diode temperature was varied between 8°C and 21°C to optimize the pump wavelength for maximum absorption at different pump currents. Our pump module is arranged for 24 passes through the gain medium and a pump spot diameter of 1.2 mm.

3. Experimental setup

The experimental setup of the laser is shown schematically in Fig. 1. The Yb:Lu_2O_3 laser head is used as a folding mirror inside a standing-wave cavity. Self-starting passive mode locking is achieved using a SESAM as an end mirror of the laser cavity. We used two different SESAMs to achieve the highest efficiency and shortest pulse duration. The SESAMs consist of a 30-pair GaAs/AlAs Bragg mirror with one or two InGaAs quantum well absorber layers respectively, which are embedded into $\lambda/2$ GaAs top layers in an antiresonant design [3].

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A set of 5 dispersive mirrors was inserted into the cavity to introduce ≈-5500 fs^2 of negative group delay dispersion (GDD) per cavity roundtrip. A 3-mm thick fused silica plate inserted at Brewster's angle ensures linear polarization of the laser output and introduces a nonlinear Kerr shift for stable soliton mode locking [17]. The pulse duration can be optimized by moving this Brewster plate along the axis of the divergent beam to control the nonlinearity inside the resonator. The best performance was obtained using an output coupling with 5.2% transmission at the lasing wavelength of 1034 nm.

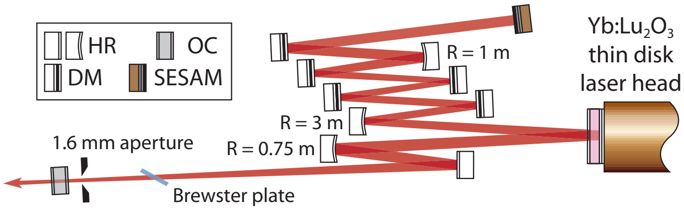

Fig. 1. Schematic of the $Yb:Lu_2O_3$ laser cavity (not to scale). Five dispersive mirrors introduce a total GDD of ≈-5500 fs^2 per cavity roundtrip. The Brewster plate has a thickness of 3 mm and the diameter of the aperture near the 5.2% output coupler is 1.6 mm. HR: highly reflective mirror, DM: dispersive mirror, OC: output coupler, SESAM: semiconductor saturable absorber mirror.

The wedge of the $Yb:Lu_2O_3$ disk was not large enough to fully separate residual reflections from the AR coating of the disk from the main beam. This residual reflection generated a much weaker beam that propagated nearly parallel to the main beam towards the output coupler. The estimated energy of this residual beam was <0.2%, which still resulted in a clearly visible modulation in the measured optical spectrum. The frequency of this modulation was ≈0.29 THz, suggesting a satellite pulse spaced by 3.4 ps from the main pulse, as is expected from a double-pass of a residual reflection through the disk. This residual reflection did not affect the mode locking stability of the laser. To remove this beam from the laser output, we inserted a 1.6-mm aperture into the cavity near the output coupler. We were successful in blocking this residual beam, which also removed the modulation in the spectrum. Because of the small beam diameter (<500 μm) near the output coupler, no clipping of the main beam and thus no measurable loss of laser output power was observed. Using a slightly larger wedge of the disk will make this aperture obsolete in future $Yb:Lu_2O_3$ thin disk lasers.

4. Experimental results

We obtain self-starting passive mode locking with 370-fs pulses at an average power of 20.5 W (Fig. 2) when using a SESAM with the measured modulation depth of 2%, non-saturable losses of ≈0.12% and a saturation fluence of 19 $\mu J/cm^2$ [18]. With the maximum incident pump power of 56 W, the optical-to-optical efficiency is 36.6%. The $sech^2$-pulses are nearly transform-limited with a spectral bandwidth of 3.4 nm centered near 1034 nm. The time-bandwidth product is 0.35 (ideal: 0.315). The repetition rate of the laser is 65 MHz, resulting in a pulse energy of 0.32 μJ and a peak power of 0.75 MW. The beam quality is nearly diffraction-limited with a measured M^2-value below 1.1.

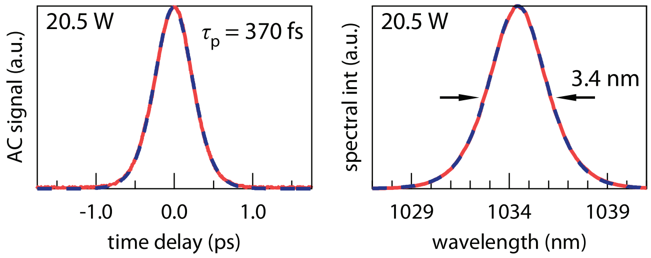

Fig. 2. Autocorrelation (left) and optical spectrum (right) of the laser output at 20.5 W of average power. The dashed lines are fit-curves with an ideal *sech*^{2}-shaped pulse of 370 fs duration and an optical bandwidth of 3.4 nm. The soliton pulses are nearly transform-limited with a time-bandwidth product of 0.35 (ideal: 0.315).

Previously, we have observed that stable mode locking can be achieved with multiple pulses simultaneously oscillating in the thin disk laser cavity [4,19]. Therefore, additional measurements were required to confirm that we really had single-pulse operation, which leads to the high pulse energy and peak power desired for further applications. We hence used an autocorrelator with a scanning range of 80 ps and a sampling oscilloscope with an 18.5-ps photo-diode to trace the pulse train. In addition, we measured the efficiency of second-harmonic generation (SHG) in a 5-mm long critically phase-matched LiB_3O_5 (LBO) crystal. In the regime of low conversion, the conversion efficiency increases linearly with the incident pump power. Operation of the laser with multiple pulses can easily be detected, because, compared with single pulse operation, it significantly lowers the conversion efficiency due to the reduced peak power. Our measurements confirmed that we had single pulse operation of the laser.

Using a SESAM with a lower modulation depth of 0.9%, we obtain an even higher output power of 24 W (Fig. 4). This SESAM has a saturation fluence of 22 $\mu J/cm^2$ and non-saturable losses of ≈0.1%. The pulses have a duration of 523 fs and a spectral bandwidth of 2.6 nm, resulting in a time-bandwidth product of 0.38 (Fig. 3). They are slightly longer because of the lower modulation depth of this SESAM, for which only a smaller gain advantage of a cw background compared to the soliton pulse can be tolerated [20]. This ultimately limits the obtainable pulse bandwidth for stable pulses and hence the pulse duration. The pulse train was again traced to confirm single-pulse operation.

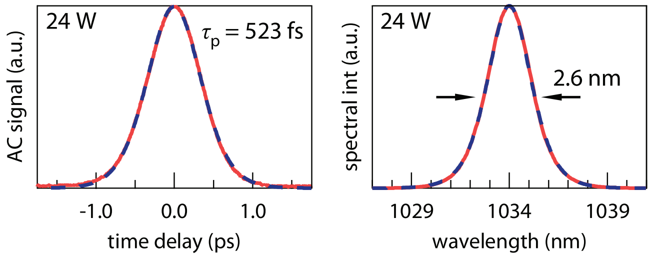

Fig. 3. Autocorrelation (left) and optical spectrum (right) of the laser output at 24 W of average power. The dashed lines are fit-curves with an ideal *sech*^{2}-shaped pulse of 523 fs duration and an optical bandwidth of 2.6 nm.

With the same repetition rate of 65 MHz the pulse energy is increased to 0.37 μJ, but the peak power is slightly lower with P_{peak} = 0.62 MW due to the longer pulse duration. Higher pulse energies and peak powers are possible by lowering the repetition rate using, e.g., a Herriott-type multiple pass cavity [21] as was demonstrated with various lasers [7,22-24].

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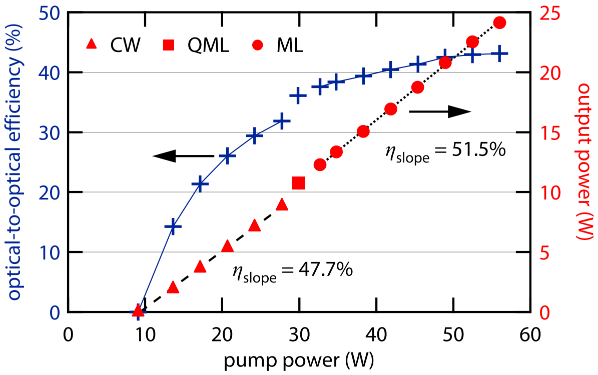

Fig. 4. Output power and optical-to-optical efficiency (crosses) of the laser as function of the incident pump power using a SESAM with $\Delta R = 0.9\%$. Stable soliton mode locking is obtained at >30 W pump power with a slope efficiency of 51.5% and the maximum optical-to-optical efficiency is 43%. CW: continuous-wave regime (triangles), QML: Q-switched mode locking regime (squares), ML: mode locking regime (circles). Dotted and dashed lines are linear fits within the respective regimes of operation to determine the slope efficiencies.

With 24 W of average power we obtain an optical-to-optical efficiency of 43% at the highest launched pump power of 56 W (Fig. 4). This is higher than the efficiency of previously mode-locked thin disk lasers. In the regime of stable mode locking, the slope efficiency is 51.5% (dotted line in Fig. 4), while below the mode locking threshold a slope efficiency of 47.7% is measured (dashed line in Fig. 4). At ≈30 W of pump power, the laser operates in the Q-switched mode locking (QML) regime (square in Fig. 4). Stable self-starting mode locking is obtained at higher pump powers and we observed no degradation of any component during many hours of operation. The output power is limited by the available pump power from the fiber-coupled laser diode.

5. Conclusion and outlook

We have demonstrated the first passively mode-locked thin disk laser based on the Yb:Lu_2O_3 gain material. It generates 370-fs pulses with 20.5 W and 523-fs pulses with 24 W of average power. An optical-to-optical efficiency as high as 43% is reached, which is higher than the efficiency of previous mode-locked thin disk lasers. The output pulses of the laser are nearly transform-limited and the beam quality is excellent with an M^2-value below 1.1.

This highly efficient material is a promising alternative to the well established Yb:YAG gain material for high power diode-pumped laser sources in continuous-wave and, thanks to its broader amplification bandwidth, also in the short pulse operation regime. Yb:Lu_2O_3 disks with a higher doping concentration of 3 at.% have already been demonstrated in efficient cw operation [15]. The possibility of further increase is currently under investigation and is expected to allow the fabrication of thinner crystals. Moreover, with its high thermal conductivity, Yb:Lu_2O_3 is suitable for power scaling and we expect that higher average powers will be obtained in the future.

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