Femtosecond $Yb:Lu_2O_3$ thin disk laser with 63 W of average power

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We present successful power-scaling of an $Yb:Lu_2O_3$ thin disk laser to record high-power levels both in cw and mode-locked operation. In a simple multimode resonator we achieved 149 W of output power in cw operation with 73% optical-to-optical efficiency (η_{opt}). Building an 81 MHz fundamental transverse mode resonator with dispersion compensation and a semiconductor saturable absorber mirror (SESAM) for passive mode locking we achieved 63 W of average power in 535 fs pulses ($\eta_{opt}=35\%$). The output beam is nearly diffraction limited ($M^2<1.2$). The 0.78 μJ pulses with a peak power of 1.28 MW had a central wavelength of 1034 nm and were close to the Fourier transform limit. With an SESAM with a larger modulation depth we obtained pulses as short as 329 fs at 40 W average power corresponding to a pulse energy of 0.49 μJ and a peak power of 1.32 MW. © 2009 Optical Society of America

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High-power femtosecond laser sources are a key element for various applications in industry as well as in high-field science. Semiconductor saturable absorber mirror (SESAM) [1] mode-locked thin disk lasers achieve higher power levels and pulse energies than other femtosecond laser oscillators owing to their power scaling potential [2]. So far, Yb:YAG based ultrafast thin disk lasers reached average powers of up to 80 W [3] and pulse energies as high as 25.9 μJ [4]. They are well suited to drive high-field experiments such as photoelectron imaging spectroscopy at multimegahertz repetition rate, where they significantly reduce the measurement time and increase the signal-to-noise ratio [5]. Furthermore, they are attractive for frequency conversion into the vacuum-UV/extreme-UV spectral range via high-harmonic generation (HHG). Currently, most HHG experiments rely on complex Ti:sapphire amplifier systems, which operate at a kilohertz repetition rate and a few watts of output power. The higher average power and repetition rate of ultrafast thin disk lasers can result in substantially higher average photon flux in the high harmonics [6].

Most ultrafast thin disk lasers are currently based on Yb:YAG as gain material owing to its good thermomechanical properties and the well-established growth technique. However, the emission bandwidth of Yb:YAG supports only pulse durations around 700 to 800 fs in mode-locked thin disk operation, which is not sufficient for experiments in many areas. So far, thin disk lasers in high-field science applications require additional temporal pulse compression [5]. Nevertheless, there are numerous other Yb-doped host materials, which appear better suited than Yb:YAG for the generation of short pulses from a thin disk laser [7]. Sesquioxide materials, such as $Yb:Lu_2O_3$ and $Yb:Sc_2O_3$, are particularly attractive, as they combine a large emission bandwidth with good thermomechanical properties. Unprecedented slope efficiencies of 80% and optical-to-optical efficiencies over 73% have been demonstrated in multimode cw thin disk operation [8,9]. The key to such a performance was a substantial increase in crystal quality, which became possible by improving the heat exchanger method for the growth of these materials [10]. Among the different sesquioxides, the host crystal Lu_2O_3 is an ideal candidate for Yb^{3+} doping. Owing to the very small mass difference, a ytterbium ion almost perfectly replaces a lutetium ion, leading to a nearly unaffected thermal conductivity compared with the undoped host Lu_2O_3 [11], which is crucial for pumping at high power levels. The absorption bandwidth of $Yb:Lu_2O_3$ at the zero-phonon line (976 nm) is 2.5 nm (FWHM).

The first mode-locked thin disk laser based on $Yb:Lu_2O_3$ achieved 24 W of average output power and an optical-to-optical efficiency of 43%, which is to the best of our knowledge the highest efficiency obtained from a femtosecond thin disk laser. Furthermore, pulses as short as 370 fs have been achieved at an average power of 20.5 W [12]. In the following we present the successful power scaling of these results by applying the scaling laws for thin disk lasers. The pump spot diameter was increased from 1.2 mm to 1.9 mm, which allowed pumping at higher power levels while maintaining comparable pump power densities.

For the cw and mode-locking experiments, we used two different $Yb:Lu_2O_3$ disks with the same specifications: a thickness of ≈250 μm, a Yb^{3+} doping concentration of 2 at.%, and a small wedge of approximately 0.05°. The back side of each disk is coated with a high-reflective (HR) coating for both pump and laser wavelength, whereas the front side has an antireflective (AR) coating for the same spectral range. The HR sides of the disks are soldered with indium-tin onto water-cooled copper-tungsten heat sinks. The disks were pumped with a fiber-coupled laser di-

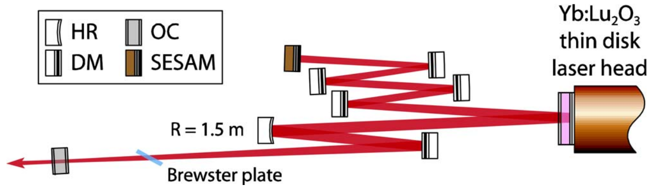

Fig. 1. (Color online) Setup of the 81 MHz $Yb:Lu_2O_3$ thin disk laser cavity used for the mode-locking experiments (not to scale). Five dispersive mirrors introduced a total negative GDD of $\approx -5500\ fs^2$ per round trip. The Brewster plate has a thickness of 2 mm. HR, curved highly reflective mirror; DM, dispersive mirror; OC, output coupler; SESAM, semiconductor saturable absorber mirror.

ode emitting at 976 nm. Wavelength stabilization and the necessary narrow emission bandwidth of the diode are achieved with a volume Bragg grating [13,14], resulting in an emission bandwidth of 0.6 nm (FWHM). The pump module was aligned for 24 passes through the disk and a pump spot size of 1.9 mm in diameter.

First, we built a simple 72-mm-long multimode resonator consisting of one of the disks and a curved output coupling mirror with a radius of curvature of 100 mm and a transmission of 2.7%. In this configuration we obtained an output power of 149 W at an incident pump power of 204 W. To our knowledge this is the highest output power that has ever been obtained with $Yb:Lu_2O_3$ and corresponds to an optical-to-optical efficiency of 73%.

For the mode-locking experiments we designed a fundamental mode cavity, which is shown schematically in Fig. 1. It contained the other $Yb:Lu_2O_3$ thin disk as a folding mirror, one curved mirror, and a set of five dispersive mirrors, introducing a total negative group delay dispersion (GDD) of $\approx -5500\ fs^2$ per cavity round trip. The cavity was 1.9 m long, which corresponds to a repetition rate of 81 MHz. An SESAM was used as one of the cavity end mirrors and is based on an antiresonant design [1,15] with a 30-pair GaAs/AlAs Bragg mirror and an InGaAs quantum-well absorber layer. Different SESAMs have been used for the mode-locking experiments as described below. The SESAM provided self-starting and stabilization of soliton mode locking [16]. A 2-mm-thick fused-silica plate introduced at Brewster's angle ensured linear polarization of the laser output and acted as the Kerr medium for the self-phase modulation required in soliton mode-locked lasers.

In a first experiment we used an output coupler with a transmission of 4.5% at the laser wavelength. The SESAM had a saturation fluence of 80.7 $\mu J/cm^2$, a modulation depth of 1.45%, and nonsaturable losses of 0.48%. We obtained self-starting passive mode locking with an average power of 40 W and pulses as short as 329 fs (Fig. 2, left) for 140 W of incident pump power. The spectrum of the pulses was centered at 1035 nm and had a FWHM bandwidth of 3.6 nm, corresponding to a time-bandwidth product of 0.331 (ideal 0.315). We believe these are the shortest pulses that have ever been obtained from a mode-locked $Yb:Lu_2O_3$ thin disk laser. The disk was wedged in order to avoid overlapping of residual reflections from the AR-coated side of the disk with the main beam. However, a wedge angle of 0.05° was too small for a complete separation of these beams. This resulted in a small modulation of the measured optical spectrum (Fig. 2 inset, left) caused by the overlap of the main beam with a residual reflection delayed by twice the thickness of the disk. Nevertheless, this wedge was sufficiently large to prevent mode-locking instabilities during the build-up phase, and we also observed no mode-locking stability degradation at steady-state operation.

In a second experiment we used an SESAM with an additional dielectric top coating and a saturation fluence of 46 $\mu J/cm^2$, a modulation depth of 0.58%, and negligible nonsaturable losses of 0.1%. Furthermore, we increased the output coupling rate to 5.4%. In this configuration we obtained a maximum average output power of 63 W at 180 W incident pump power (6.3 kW/cm^2), corresponding to an optical-to-optical efficiency of 35%. The pulses had a duration of 535 fs and a spectral bandwidth of 2.3 nm centered around 1034 nm (Fig. 2, right). This yields an almost

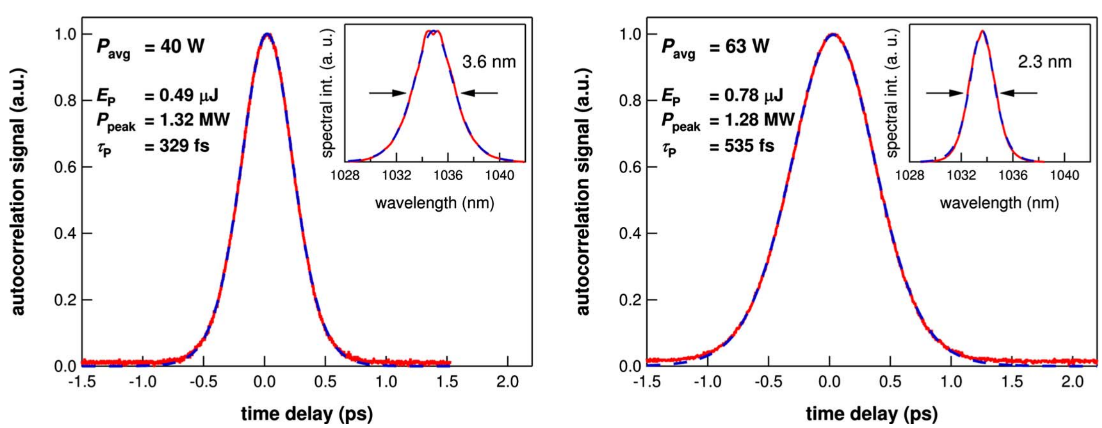

Fig. 2. (Color online) Autocorrelation and optical spectrum (inset) of the measured pulses [solid curves (red online)] with fit curves assuming ideal $sech^2$ pulses [dashed curves (blue online)]. The laser had a repetition rate of 81 MHz. Left, the shortest pulses had a duration of 329 fs and a spectral bandwidth of 3.6 nm centered at 1035 nm measured at an output power of 40 W. Right, the highest output power of 63 W was achieved in 535 fs long pulses with a spectral bandwidth of 2.3 nm centered near 1034 nm.

transform-limited time-bandwidth product of 0.345 (ideal 0.315). The beam was close to the diffraction limit with a measured M^2 value of 1.2. At a lower pump power of 148 W, corresponding to a pump power density of 5.2 kW/cm^2, the highest optical-to-optical efficiency of 37% was obtained. The decrease in efficiency for pump power densities above this value is most likely due to a thermal rollover. A further increase of the pump spot diameter to 2.8 mm as in [17] would result in a roughly two times larger pumped area. According to the scaling law for thin disk lasers an average output power exceeding 100 W could be expected.

In summary, we successfully applied the scaling principle for passively mode-locked thin disk lasers by expanding the pump spot diameter from 1.2 mm to 1.9 mm and increasing the pump power from 56 W to 180 W. This led to an average output power of 63 W, which is almost a factor of 3 higher than the previously reported result [12]. At somewhat lower average output power of 40 W we obtained pulses as short as 329 fs. These results clearly demonstrate that Yb:Lu_2O_3 is an excellent alternative for high-power ultrafast lasers, supporting similar power levels and shorter pulse durations than ultrafast thin disk lasers based on Yb:YAG.

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