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A 12.1-W SESAM mode-locked Yb:YAG thin disk laser*

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Pumped by a 940 nm fiber-coupled diode laser, a passively mode-locked Yb:YAG thin disk oscillator was demonstrated with a semiconductor saturable absorber mirror (SESAM). 12.1 W mode-locked pulses were obtained with pulse duration of 698 fs at the repetition rate of 57.43 MHz. Measurement showed that the beam quality was close to the diffraction limit.

Keywords: high power, semiconductor saturable absorber mirror (SESAM) mode-locked laser, thin disk

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1. Introduction

Ultrafast lasers providing high average powers have become a promising tool for scientific research and industrial applications, such as strong-field physics, nonlinear wavelength conversion, and high-speed and high-precision micromachining. Up to now, watt-level femtosecond oscillators have been demonstrated based on bulk gain media such as Yb:KGW,[1] Yb:CaF_2,[2] and Yb:YAG ceramics.[3] However, the increasing of the output power is limited by the thermal effect in the bulk ceramics and crystals. The rise of the temperature is a crucial problem for the bulk gain media to generate ultrafast pulses with high average power and good beam quality. In addition, the thermal lens effect is detrimental on quasi-three-level systems to obtain the highest power efficiency under high pump-power densities. To improve the thermal management of the gain media, many new techniques, such as thin disk, fiber,[4,5] and slab[6] systems, have appeared, and by using those techniques, the power has been successfully increased to the hundred-watt level.[7–9] Compared with the other two geometries, the thin disk structure is of more benefit to obtaining kilowatt power by increasing the pump diameter or by using several crystal disks.[10]

In contrast to the bulk oscillators, the thin disk concept[10,11] is based on a thin ($\approx$ 200 μm) and large diameter (> 5 mm) gain medium, one of whose surfaces is directly mounted on a water-cooled heat sink. Because of the large ratio between the diameter and the thickness of the disk, the heat flow along the beam axis is nearly one-dimensional, which leads to small thermal distortions and aberrations even at very high pump power. The thin disk oscillators allow both high power and good beam quality because of their excellent heat removal capabilities. Combining with the passively mode-locked technique, the thin disk concept provides an approach to achieve high-power ultrafast pulses without additional amplifier stages. In 2000, Aus der Au *et al.* demonstrated a passively mode-locked Yb:YAG thin disk laser with an output power of 16.2 W for the first time.[12] Now this technique has stepped into the average power and pulse energy frontiers obtained from ultrafast oscillators. Average power up to 275 W,[9] shortest pulse duration of 730 fs[12] (in atmospheric air), and pulse energy of 80 μJ[13] were demonstrated using semiconductor saturable absorber mirror (SESAM) mode-locked Yb:YAG thin disk oscillators. Pronin *et al* obtained 200-fs pulses from a Kerr-lens mode-locked Yb:YAG thin disk oscillator with an average power of 17 W.[14] SESAM-mode-locked thin disk lasers (TDLs) currently achieve higher pulse energies and average powers than any other ultrafast oscillator technology. Along with the development of the thin disk technology, many different crystals have been proved to be potential candidates for thin disk gain materials, such as Yb:LuScO,[15–17] Yb-doped cubic sesquioxides,[18–20] tungstate materials,[21,22] and Yb:YCOB.[23]

It is noticeable that Yb:YAG is widely used as the thin disk crystal because it can be grown with high quality and in large sizes. In addition, it is characterized by good thermal conductivity ($\sim$ 7 W/(m·K)) and wide absorption and emission bands, which are necessary factors to generate high average power. In this work, we demonstrated a compact passively mode-locked femtosecond Yb:YAG thin disk oscillator by SESAM. In order to increase the nonlinearity in the cavity, a 2-mm-thick Brewster plate was positioned at the focus point of two concave mirrors, whose radii of curvature are 150 mm and 200 mm, respectively. By using this asymmetrical and

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tight focus cavity structure, large laser mode on the thin disk and compact cavity design were obtained at the same time.[24] This asymmetrical cavity design makes it possible to obtain a high repetition rate by using the thin disk laser. High repetition rate and high power ultrafast lasers are good tools for UV-XUV and MIR frequency comb spectroscopy. By optimizing the cavity, 12.1 W average output power of 698-fs pulses was obtained under the pump power of 55 W with an optical-to-optical efficiency of 22%.

2. Experimental setup

In the experiment, a 220-μm-thick 7 at.% doped Yb:YAG disk was used as the gain medium. One surface of the thin Yb:YAG disk coated for high reflectivity at both the laser and the pump wavelengths was directly mounted on a water-cooled heat sink, and the other surface had an antireflection coating. A fiber-coupled laser diode (LD) emitting at 940 nm with an output power of 70 W was used as the pump source. The pump laser spot aligned on the disk has a diameter of 2.3 mm, which is much larger than the thickness (220 μm) of the crystal. To avoid the damage caused by residual reflections of the pump power from the antireflection coating, the disk was slightly wedged. Due to the very small thickness of the disk, the single-pass pump absorption is limited to a few percent (of the order of 10%) at the typical doping level. In order to overcome this limitation, a multiple pump pass arrangement should be used. Figure 1 shows the pump design for 24 passes. The collimated pump beam is focused into the crystal by a parabolic mirror. The thin disk crystal is positioned in the middle of the focal plane. After 24 passes of the pump laser through the disk, above 80% of the pump power will be absorbed by the disk.

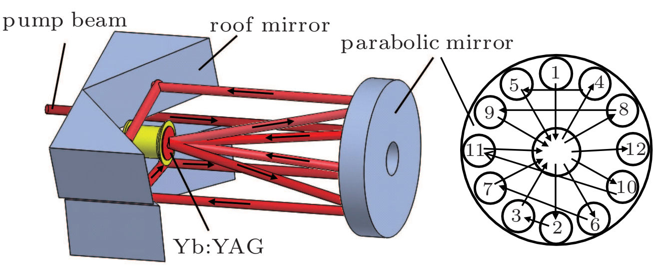

Fig. 1. (color online) Pump design for 24 absorption passes. The sequence of the segments on the parabolic mirror used as the pump laser traverses through the setup is indicated by numbers 1–12.

Figure 2(a) shows a typical Z-shape cavity design, where the disk is served as a folded mirror and is positioned near mirror M2. The radii of mirrors M1 and M2 are 150 mm and 200 mm, respectively, which lead to a large laser mode size on the crystal. For fundamental mode operation, the calculated laser mode radius on the disk is about 2 mm. By using this asymmetrical cavity design, it is possible to achieve a large laser mode on the disk without using mirrors of long focal length.

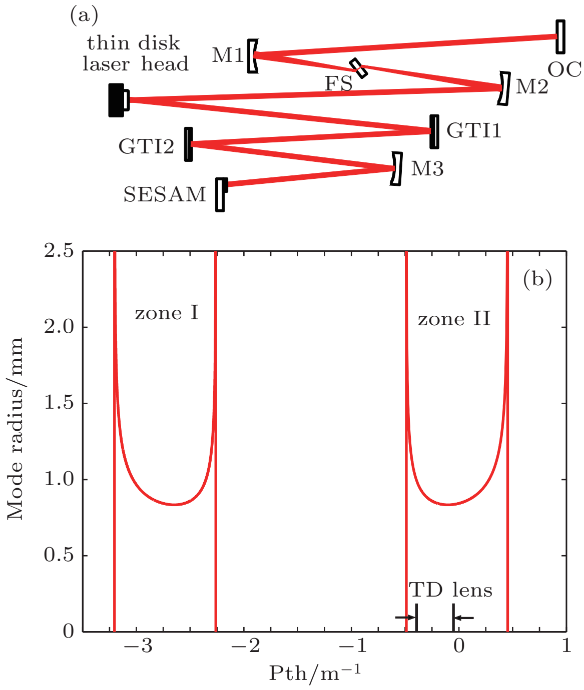

Fig. 2. (color online) (a) Schematic of the Yb:YAG thin disk oscillator. M1, M2, and M3 are the concave mirrors with radii of curvature of 150 mm, 200 mm, and 500 mm, respectively; GTI1 and GTI2 are Gires–Tournois interferometer mirrors; OC is an output coupler with 2.5% transmission; FS is a 2-mm-thick fused silica plate positioned at the Brewster angle; and SESAM represents the semiconductor saturable absorber mirror. (b) Mode radius on the thin disk vs. the dioptric power of the thin disk.

The thermal lens seems to be the most crucial limitation for high power operation. This problem is partly solved by using a thin disk gain medium. The influence of the thermal lens on the resonator mode and stability was demonstrated by Magni.[25] We analyzed the mode radius on the disk under the influence of the dioptric power of the thermal lens. The ABCD analysis of this cavity (Fig. 2(a)) shows two stability zones arising as a function of the dioptric power of the thin disk thermal lens. The variation of the mode radius on the thin disk with the dioptric power of the thin disk is shown in Fig. 2(b). At near-zero pump power, the thin disk has a dioptric power of −0.4 1/m (One surface of the thin disk is initially designed to be concave with a radius of curvature of around 5 m, as specified by the supplier). Thus the unpumped oscillator is located close to the edge of stability zone II and pumping brings it to the middle of the stability zone. The beam waist on the disk is nearly constant during the pump increasing process, which means good dynamic stability of the resonator and good mode matching.

For soliton mode-locking, a 2-mm-thick fused silica plate was positioned at the focus point of two curved mirrors with Brewster angle to introduce the self-phase modulation (SPM) and to achieve the linear polarization of the laser mode. Two

Gires–Tournois interferometer mirrors, generating a total negative GDD of 4000 fs^2 per round trip, balanced the SPM phase shift. Another curved mirror with a radius of curvature of 500 mm in the cavity was used to increase the fluence on the SESAM. For starting and stabilizing the mode-locking, a SESAM (BATOP GmbH) with 1 ps relaxation time and $< 0.7\%$ modulation depth was used in the experiment. The laser mode radius on the SESAM is calculated to be ≈ 150 μm.

3. Results and discussion

To carry out the experiment, we first used a high reflection mirror to align the laser cavity. With a 2.5%-transmission output coupler, we obtained the maximum CW average power up to 25.2 W with a fundamental laser mode, corresponding to an optical-to-optical efficiency of 35.2%. Then a stable mode locking operation was obtained by replacing the high reflection mirror with a SESAM. The average power of the mode-locked pulses in single mode operation ($M^2 < 1.1$) could rise from 4.77 W to 12.1 W by increasing the pump power, corresponding to a slope efficiency of 35%. Figure 3(a) shows the variation of the output power with the increase of the pump power. Further increasing the pump power to over 60 W, SESAM damage was observed in the experiment.

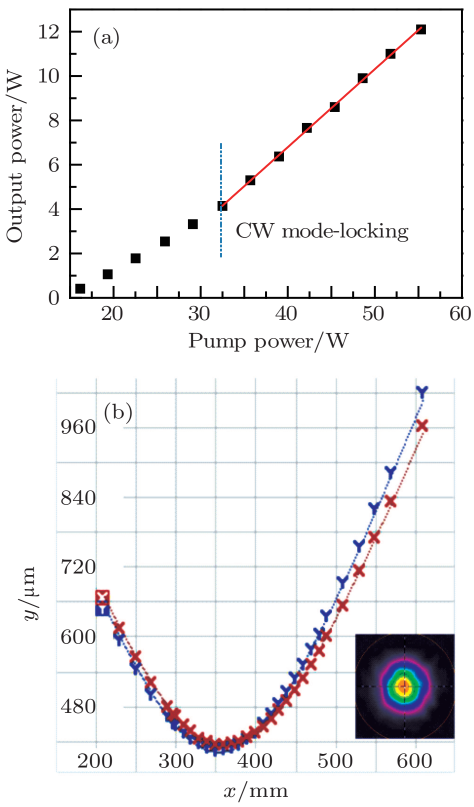

Fig. 3. (color online) (a) The variation of output power with pump power. (b) The M^2 factors and the beam profile (inset) of mode-locked operation.

The beam quality of the mode-locked operation at the average power of 12.1 W was measured by a commercial M^2 factor meter (Spiricon M2-200s), as released in Fig. 3(b). The M^2 factors in the mode-locked operation are 1.05 and 1.07 for the tangential and sagittal directions, respectively. The beam profile is shown in the inset of Fig. 3(b), which implies a near fundamental mode operation.

The stable mode-locked pulse train is shown in Fig. 4, which was measured with a 500-MHz digital oscilloscope and a high-speed PD detector. The intensity autocorrelation trace of the pulses was also measured by a commercial intensity autocorrelator (FR-103MN, Femtochrome Research, Inc.) in this case (Fig. 5(a)). The pulse duration is 698 fs if a sech^2-pulse shape is assumed. The mode-locked optical spectrum is shown in Fig. 5(b) with a full width at half maximum (FWHM) bandwidth of 1.9 nm. The corresponding time–bandwidth product is 0.39 (sech^2-shape pulse, ideal 0.315), indicating a few chirps during the mode-locking operation.

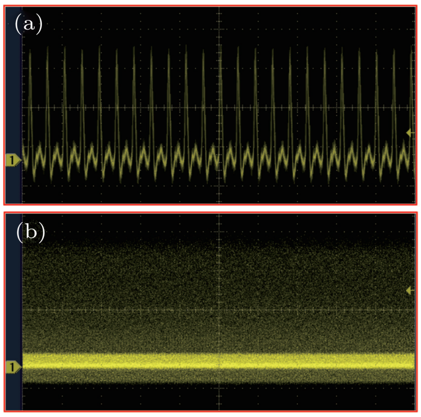

Fig. 4. (color online) Mode-locked pulse train in the timescales of (a) 40 ns/div and (b) 400 μs/div.

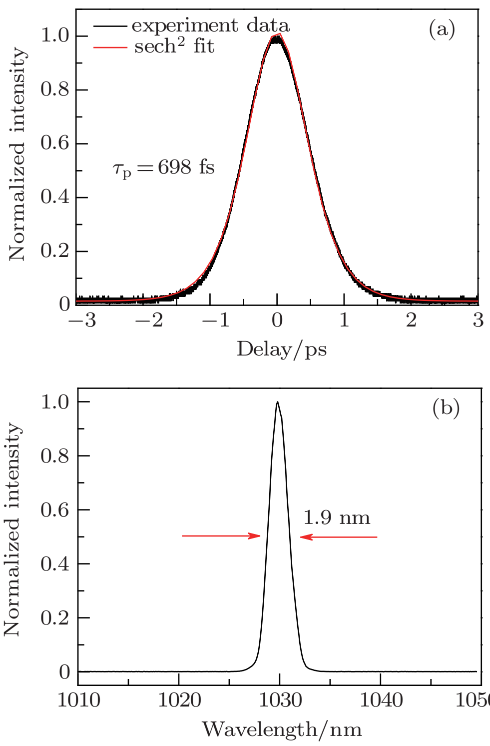

Fig. 5. (color online) (a) Pulse duration of the SESAM mode-locked Yb:YAG thin disk oscillator. (b) The corresponding laser spectrum.

The radio frequency (RF) of the mode-locked pulses was measured with an RF spectrum analyzer (Agilent E4407B). As shown in Fig. 6(a), the fundamental beat note is at 57.43 MHz with an extinction ratio down to 65 dBc with a resolution bandwidth of 1 kHz, which indicates that the laser is in a stable mode-locking operation. Figure 6(b) shows the high harmonics of the fundamental beat note at a wide span from 0 to 1 GHz. Note that the decrease of the harmonics is caused by the frequency response curve of our PD detector, rather than the instability of the mode-locking.

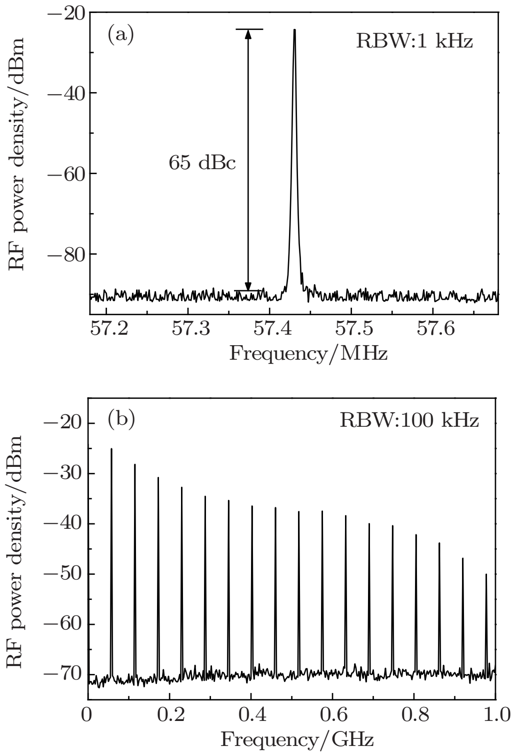

Fig. 6. Radio frequency spectrum of the SESAM mode-locked Yb:YAG thin disk laser. (a) RF spectrum at the fundamental beat note with the RBW of 1 kHz. (b) RF spectrum of 1 GHz wide-span range with the RBW of 100 kHz.

In our experiment, a crucial issue for high power operation was the damage to the SESAM. The damage was always caused by the mode-locking instability and the corresponding high peak intensity during the pulse build-up process. In addition, the low damage threshold (~ 4 mJ/cm^2) was another important reason for easy damage in high power operation. Relevant study showed that the damage at high fluences occurs due to heating of the lattice by the inverse saturable absorption (ISA), rather than the specific design of the absorber section.[26] So high power TDLs require the SESAMs with high damage threshold, large saturation fluencies, and reduced ISA. By using multiple QWs and a suitable dielectric top-section, the SESAMs with $< 0.1\%$ nonsaturable losses and reduced ISA could withstand pulse fluences > 0.2 J/cm^2.[27] With high damage threshold SESAM, kilowatt mode-locking thin disk oscillators would be obtained by power scaling. In our experiment, to obtain higher output power, we should optimize the starting regime of the oscillator and enlarge the laser mode on the SESAM. In the future, high pump power will be used to generate higher average power by enlarging the mode size both on the thin disk and the SESAM.

4. Conclusion

We presented a stable passively mode-locked Yb:YAG thin disk oscillator with a SESAM. An average output power as high as 12.1 W with 698 fs pulse duration was obtained at a repetition rate of 57.43 MHz. The central wavelength was 1030 nm with a spectral bandwidth of 1.9 nm. Near single fundamental mode with beam quality of $M^2 < 1.1$ was realized. The Yb:YAG thin disk oscillator will be a potential candidate for high power and good beam quality laser source.

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