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Generation of 15 W femtosecond laser pulse from a Kerr-lens mode-locked Yb:YAG thin-disk oscillator*

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We demonstrated a robust power-scalable Kerr-lens mode-locked (KLM) operation based on a Yb:YAG thin-disk oscillator. 15-W, 272-fs pulses were realized at a repetition rate of 86.7 MHz with an additional Kerr medium and a 2.5 mm hard aperture in the cavity. 247-fs pulses with an average power of 11 W could also be obtained by using a 2.4 mm hard aperture. Based on this shorter pulse, high efficient second-harmonic generation (SHG) was performed with a 1.7-mm-long LiB_3O_5 (LBO) crystal. The SHG laser power was up to 5 W with the power fluctuation RMS of 1% measured over one hour.

Keywords: thin disk, Kerr-lens mode-locking, high power, second harmonic generation

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1. Introduction

In recent years, ultrafast thin-disk lasers have attracted increasing attention due to their excellent characteristics, such as high average power, excellent beam quality, and power-scalable capability. The demands for high-average-power femtosecond laser sources motivate the rapid development of the thin-disk technology, which paves the way for providing an unprecedented versatility and variety of methodologies for ultrafast spectroscopy and nonlinear optics. A 16-W, 730-fs SESAM mode-locked Yb:YAG thin-disk oscillator was first demonstrated by Keller and co-workers in 2000.[1] Subsequent advances led to the highest average power of 275 W,[2] the shortest pulse duration of 49 fs,[3] the highest pulse energy of 80 μJ,[4] and the highest repetition rate of 260 MHz[5] directly from the oscillators. These advances open up the prospect of the mode-locked thin-disk oscillators as the third generation femtosecond sources, which combine high peak powers with high average powers.[6] For instance, the high-power mode-locked lasers based on thin-disk technology have already been successfully used as the source lasers for frequency-comb spectroscopy[7,8] and optical parametric (chirped pulse) amplification.[9–12]

The semiconductor saturable absorber mirror (SESAM) mode-locking technique has been widely used in thin-disk lasers to generate femtosecond pulses. The pulses with 275 W output power[2] and 80 μJ pulse energy[4] have been obtained based on Yb:YAG thin-disk oscillators. However, the pulse durations are limited to 600 fs, which are much longer than the Fourier-transform-limited (supported by the Yb:YAG gain medium). The KLM technique has been proved to be a potential method to support much shorter pulse duration because of its short relaxation time and high modulation depth. In 2011, Pronin *et al.* demonstrated the first KLM thin-disk laser with 200 fs pulse duration and 17 W output power based on Yb:YAG.[13] Recently, a KLM Yb:YAG oscillator operated in atmosphere air yielded an average power of 270 W in 330 fs by enlarging the cavity mode in the Yb:YAG disk and Kerr medium together.[14] Thanks to the excellent performance of the KLM thin-disk oscillators, compact thin-disk-based high-power, good-beam-quality femtosecond green sources have powered numerous scientific and technological applications, such as pumping of optical parametric oscillators,[15] spectroscopy,[16] and material processing.[17]

In this paper, a high-power KLM oscillator based on Yb:YAG thin-disk crystal is reported. With a 2-mm-thick FS plate and a 2.5-mm pinhole, stable mode-locking operation was obtained with pulse durations of 272 fs. Pumped by a 940-nm, 70-W laser diode, the system obtained an output power of 15 W, corresponding to an optical conversion efficiency of 21%. With a 2.4 mm hard aperture, a shorter pulse of 247 fs could be achieved with 11 W output power. In this case, 60% conversion efficiency of the second harmonic generation (SHG) was achieved by using a 1.7-mm-long LiB_3O_5 (LBO) crystal. Owing to the good beam quality of the fundamental mode, a green laser beam near diffraction limit was observed and the measured RMS power fluctuation was 1% over one hour. The conversion efficiency and the laser beam profile obtained from our experiment are superior to the other fem-

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tosecond green laser systems.[18,19] This compact and efficient femtosecond green laser will be a good choice for pumping optical parametric oscillators and generating high power UV laser.

2. Experimental setup

Figure 1 is an illustrative view of the experiment. The pump source was a 940 nm, fiber-coupled laser diode. A thin-disk module (TDM) was used to increase the pump absorption by multipassing through the disk crystal. Moreover, the pump beam was imaged on the disk crystal with a large spot diameter of 2.3 mm. The gain medium was a 220-μm-thick, 7 at.% doped wedge Yb:YAG disk with a diameter of 9 mm. In a typical Z-shape cavity, the gain medium was used as a folded mirror. A tight focusing structure, which was composed of two plane-concave mirrors M1 and M2 with the radius of curvature (ROC) of 150 mm, contributed to enhance the Kerr-lens effect and increase the interacavity density. In order to obtain more power and minimize the risk of damage to the cavity mirrors, the cavity was designed for large mode sizes both on the mirrors and the Yb:YAG thin disk. To enhance the Kerr-lens effect, a fused silica Brewster plate was inserted at the focus points of the two curved mirrors. Besides a high optical damage threshold, the fused silica has an excellent optical performance with $n_2 = 2.5 \times 10^{-20}$ m^2/W, which is often used as the Kerr medium.

Two flat high-dispersive mirrors were employed to compensate the nonlinear phase shift of the optics components and the air. The two mirrors have a GDD of -3000 fs^2 over the wavelength range of 1027–1033 nm. To initial the Kerr-lens mode-locking, the oscillator operated at the edge of the stability zone by increasing the distance of the curved mirrors. Additionally, a hard aperture was inserted in the cavity, which was helpful for hard-aperture KLM. A wedged output coupler with 8% transmission was used.

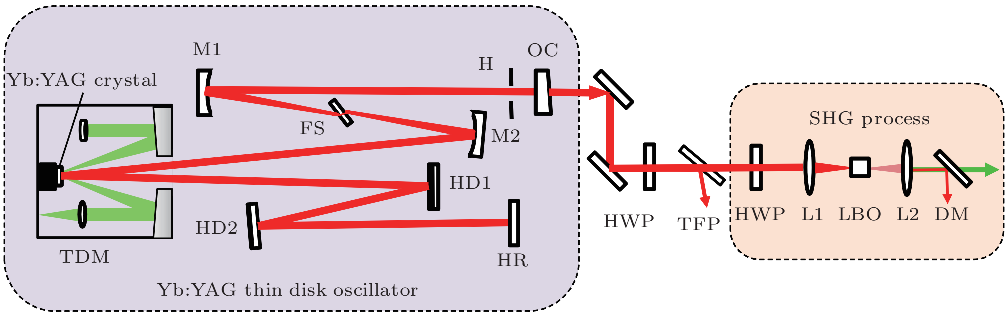

Fig. 1. (color online) Illustration of the KLM Yb:YAG thin disk laser and SHG process. TDM: thin disk module (D+G, TDM 1.0); M1 and M2: concave mirrors with the ROC of 150 mm; FS: fused silica plate positioned at the Brewster angle in the focus of M1 and M2; OC: output coupler with 8% transmission; HD1 and HD2: flat high-dispersive mirrors with GDD of -3000 fs^2 per bounce; HR: high reflective mirror; H: hard aperture; HWP: half wave plate; TFP: thin film polarizer; L1 and L2: 50 mm focal lenses; DM: dichroic mirror.

3. Results and discussion

To realize the single transverse mode operation, ABCD-matrix analysis of the cavity was made firstly. The calculated laser mode on the disk crystal was about 1.8 mm, which was slightly smaller than the spot size of the pump beam. Figure 2 presents the output power and efficiency of the oscillator under continuous wave (CW) operation. The slope efficiency of 46% was obtained. 24.2 W average power could be achieved when the pump power was increased to 71.5 W with an optical conversion efficiency of 36%. The beam profile in this case is shown in the inset.

For the KLM operation, a pinhole with a diameter of 2.5 mm was inserted into the cavity as a hard aperture, which was fixed on a copper sink to optimize the thermal management. The calculated intracavity GDD was about -12000 fs^2 per round trip. Firstly, the oscillator was operated at the edge of the stability regime by fine-tuning the position of M1. Then the KLM operation could be achieved by carefully adjusting the position of the Brewster plate and pushing the mirror HR. A 2-mm-thick Brewster plate served as the Kerr medium and the beam radius in the Kerr medium was about 50–100 μm. Under 70-W pump power, stable KLM operation was achieved with 15 W average output power. Measured by a 500 MHz digital oscilloscope and a high-speed detector, the mode-locked pulse train is shown in Fig. 3. Under this condition, the intensity autocorrelation trace was measured by a commercial intensity autocorrelator (Femtochrome Research, FR-103MN). The pulse duration was about 272 fs if a sech^2-pulse shape was assumed, as shown in Fig. 4(a). Within a time window of 500 ps, we did not observe any multi-pulse in the autocorrelation trace. For this situation, the calculated Kerr nonlinearity was about 0.5 rad (corresponding to the GDD of about -10000 fs^2 required for 272-fs pulse) per cavity round trip, which can be balanced by the GDD of -12000 fs^2 introduced in the cavity. Figure 4(b) shows the corresponding spectrum measured by a commercial spectrum analyzer (YOKOGAWA, AQ6370C). The full width at half maximum (FWHM) of the optical spectrum was about 4.5 nm, corresponding to a time-bandwidth product of 0.35.

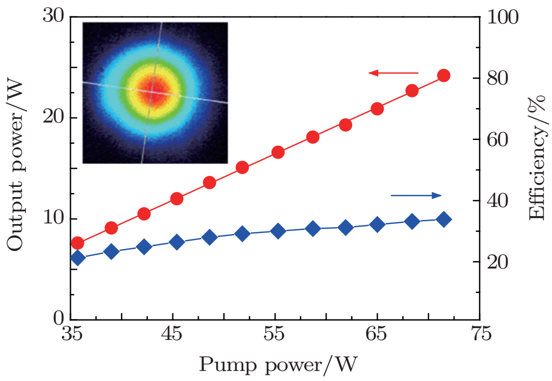

Fig. 2. (color online) Output power and efficiency of CW Yb:YAG thin disk oscillator. Inset: beam profile at 24.2 W.

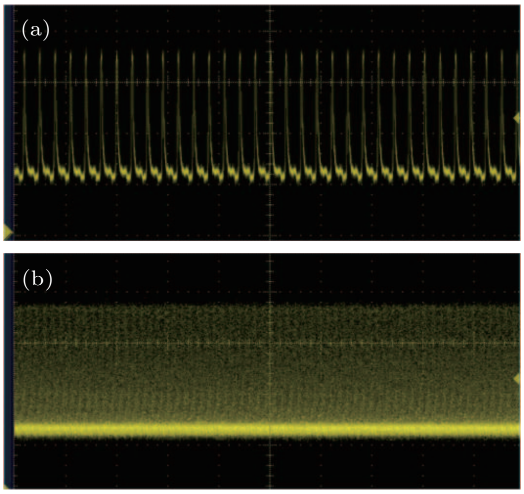

Fig. 3. (color online) KLM mode-locked pulse train in the time scales of (a) 40 ns/div and (b) 2 μs/div.

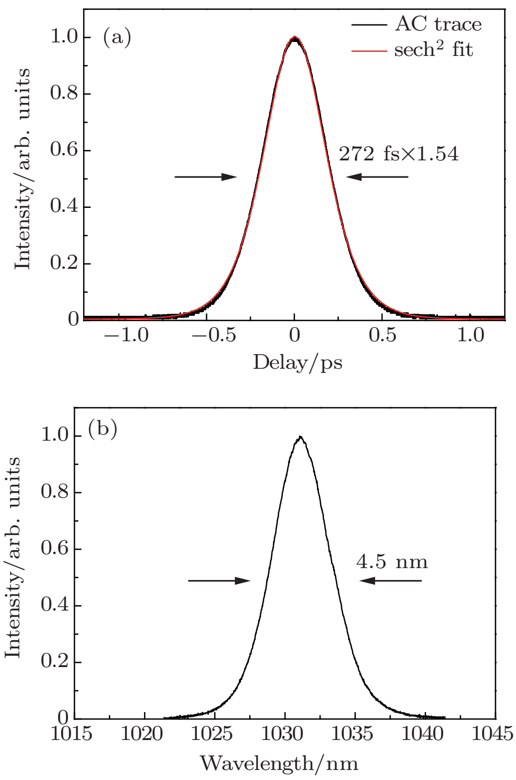

Fig. 4. (a) Measured autocorrelation trace (black) and sech^2-fitting (red) from the KLM oscillator. (b) The corresponding optical spectrum.

By using a radio frequency (RF) spectrum analyzer (Agilent E4407B), the RF spectrum of the oscillator was recorded. As shown in Fig. 5(a), the signal-to-noise ratio of the oscillator was as high as 77 dBc with 1 kHz resolution bandwidth. Figure 5(b) reveals the high harmonics of the fundamental frequency at a wide-span from 0 to 1 GHz. Note that the decrease of the harmonics was caused by the frequency response curve of our photodiode (PD) detector, rather than the instability of the mode-locking.

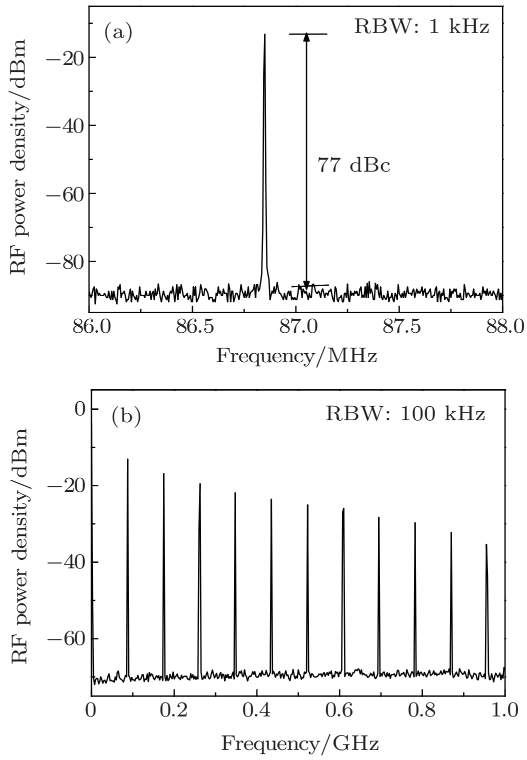

Fig. 5. RF spectra (a) at the fundamental beat note and (b) 1 GHz wide-span range of the 15 W, 272 fs Yb:YAG thin disk laser.

As we all know, it is an important issue to balance the nonlinearity and the dispersion in the cavity for soliton mode-locking. The nonlinearity phase shift in a thin-disk laser is mostly provided by the Brewster plate. In the experiment, a total amount of negative GDD about -12000 fs^2 in the cavity was introduced by the two high-dispersive mirrors. To explore the influence of the nonlinearity on the KLM operation, different Brewster plates with thicknesses of 1 mm, 2 mm, and 3 mm were used to optimize the KLM performance. Pulse durations of 505 fs, 272 fs, and 330 fs and output powers of 12 W, 15 W, and 12.8 W were achieved by different Brewster plates under 70 W, 70 W, and 65 W pump powers (Fig. 6(a)). The introduced nonlinearity was determined by the thickness of the Brewster plate, which could affect the mode-locked spectrum and pulse duration, as shown in Fig. 6(b). When a 3-mm-thick plate was employed, the very high self-phase modulation (SPM) caused by high nonlinearity could not be balanced by the introduced GDD in the cavity. Unavoidably, detected with a fast photodiode, multiple pulses were easily observed at 17 W output power and 70 W pump power. Stable single-pulse operation could be achieved by decreasing the pump power to 65 W. According to these results, the SPM caused by the Kerr medium had a crucial impact on stable and single-pulse KLM operation. With a thinner plate of 1 mm, the mode-locking regime was smaller than that with the thick plate because of its lower nonlinearity, which made it relatively difficult to obtain KLM operation. Therefore, the dispersion compensation is a crucial issue for the thin-disk laser to obtain high power. Based on the results and analysis, we foresee the shorter pulse durations obtained by finely controlling the SPM and dispersion.

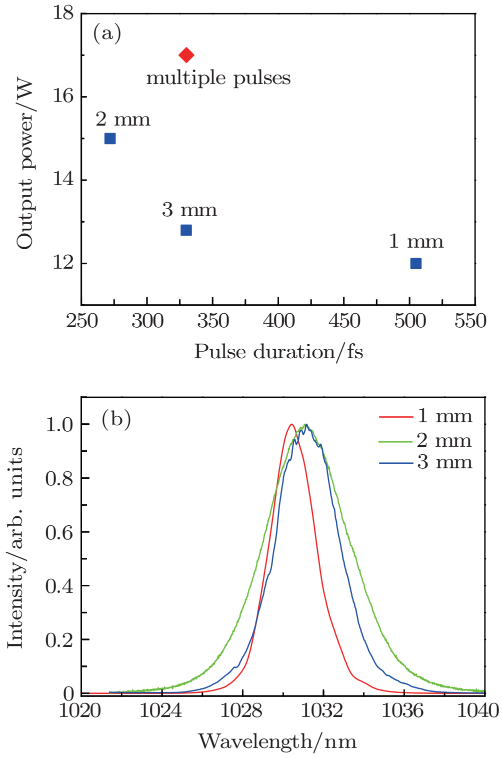

Fig. 6. (color online) (a) Experiment results and (b) spectra of the KLM operation with different Brewster plates (1 mm, 2 mm, and 3 mm).

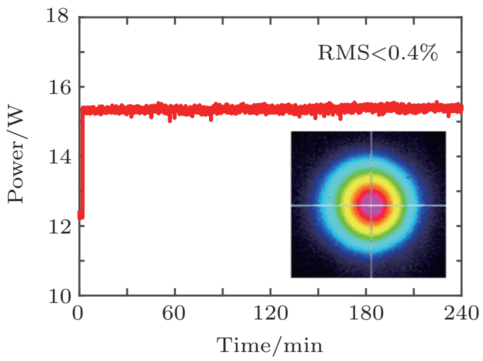

Fig. 7. (color online) Power stability of the KLM oscillator over a period of 4 h. Inset: beam profile at 15 W.

In the experiment, the KLM operation was better when using a 2-mm-thick plate. The CW operation with average power of 12.3 W was achieved under 70 W pump power. When the KLM operation was realized, the output power increased to 15 W. The KLM operation could keep stable for long terms once started. Figure 7 shows the output power stability of the KLM oscillator over a period of 4 hours. The measured RMS fluctuation is less than 0.4%. Measured by a commercial CCD camera (WinCamD-UCD15), the beam profile of the mode-locked operation is shown as an inset in Fig. 8(a).

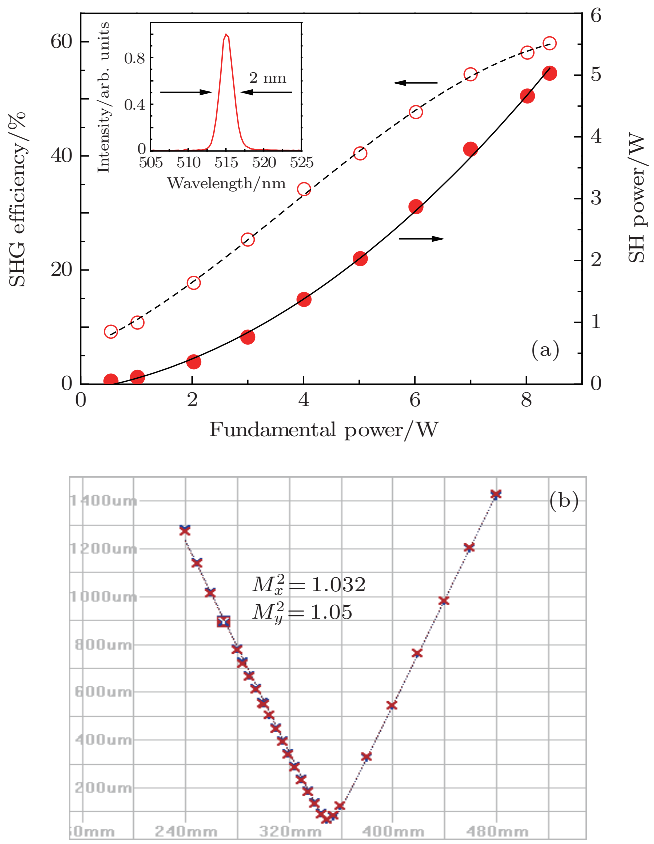

Fig. 8. (color online) (a) SH power and efficiency variation with the fundamental power. Inset: corresponding spectrum of green pulses. (b) Beam quality measurement of the frequency-doubled 515 nm beam.

In addition, we experimentally found that the modulation depth of the Kerr effect could be enlarged by reducing the size of the hard aperture, which made the pulse duration shorter. By using a 2.4 mm hard aperture, 247-fs pulse was obtained from the above oscillator with a compromised power of 11 W. The second harmonic generation was performed based on this result, which is shown in Fig. 1. To continuously vary the fundamental power, a thin-film polarizer (TFP) and a half-wave plate (HWP) were employed. Frequency doubling was obtained in an external LBO crystal for a single pass. A 1.7-mm-long LBO crystal was used for SHG with an aperture of 3 mm ×3 mm. The LBO crystal was cut at $\theta = 90^\circ$ ($\phi = 13.6^\circ$) for type I (o+o→e) critical phase-matching at room temperature. The fundamental beam was focused in the LBO crystal with a beam radius of 63 μm by a 50 mm focal lens. The generated SH beam was separated from the residual fundamental by a dichroic mirror, which was HR-coated ($R > 99\%$) at

1030 nm and AR-coated ($T > 99\%$) at 515 nm. Figure 8(a) shows the power scaling and efficiency results for single-pass SHG in LBO crystal. The SHG power of 5 W was achieved for the highest available fundamental power of 8.4 W at the input to the LBO crystal with a conversion efficiency of 60%. Figure 8(a) reveals that the conversion efficiency tended to be slightly saturated at the high input power level. The spectral characterization of the generated green laser beam is displayed as an inset in Fig. 8(a) with a FWHM bandwidth of 2 nm. The beam quality of the green laser at the average power of 5 W was measured by a commercial M^2 factor meter (Spiricon M2-200s). Owing to the good beam quality of the fundamental mode, the SHG beam quality factor M^2 was measured to be < 1.1, as shown in Fig. 8(b). In addition, the RMS power fluctuation was less than 1% over one hour.

4. Conclusion

In summary, we constructed a high-power KLM Yb:YAG thin-disk laser. By employing a 70 W diode pump laser, 15-W, 272-fs output pulses were obtained at a repetition rate of 86.7 MHz. The output pulse duration could be varied by using a hard aperture with different diameters. Based on the 247-fs, 11 W output laser, we performed the SHG process with a 1.7-mm-long LBO crystal. Up to 5 W, 60% high-efficiency second-harmonic generation at 515 nm was achieved with a TEM00 beam profile, and the measured power fluctuation RMS was as low as 1% over one hour. This work offers a promising route to implementing powerful ultrashort pulse generation at high repetition rates.

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