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High-power 55-fs Yb:YAG thin-disk oscillator at 200 MHz repetition rate

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High-repetition-rate ultrafast laser oscillators with high average power and short pulse duration provide excellent sources for generating optical frequency combs. Here we report a Kerr-lens mode locked Yb:YAG thin-disk oscillator delivering 203-MHz pulses at an average power of 9.4 W. A single additional nonlinear plate was inserted inside the cavity to enhance the Kerr lens effect, which leads to a substantial broadening of the mode-locked spectrum. The resultant pulse duration is 55 fs. The demonstrated oscillator combines a high repetition rate, a high average power and short pulse duration within one resonator, offering an ideal prerequisite for the optical-frequency metrology and frequency-comb spectroscopy with high signal-to-noise ratio.

KEYWORDS

high repetition rate, high power, ultrashort pulses, thin disk, Yb:YAG

Introduction

Ultrafast laser oscillators with high average power and short pulse duration are always pursued due to their numerous applications in many fields, such as spectroscopy [1, 2], cell applications [3], trace gas analysis [4], biological imaging [5]. Furthermore, such oscillators with high repetition rate are excellent laser sources for generating optical frequency combs. The increased power per mode under the condition of high repetition rate can improve the signal-to-noise ratio in optical-frequency metrology and frequency-comb spectroscopy [6]. Until now numerous works have been done to increase the performance of the laser oscillators towards higher average power, shorter pulse duration and higher repetition rate. Based on fiber oscillators, the repetition rate of the generated pulses can reach up to GHz, and the pulse duration can be shortened down to ~50 fs. Based on fiber oscillators, the repetition rate of the generated pulses can reach up to multi-GHz [7, 8], and the pulse duration can be shortened down to ~30 fs [9]. However, it is difficult to achieve sub 50-fs laser pulses with a high repetition rate at the same time. Moreover, the average power of the traditional ultrafast fiber oscillators is limited to milliwatts level due to the strong nonlinear effect in the fibers. Although the average power could be boosted based on large-pitch fiber oscillators, the repetition rate was restricted (<100 MHz) by the fiber length [10]. For ultrafast bulk-crystal laser oscillators, substantial

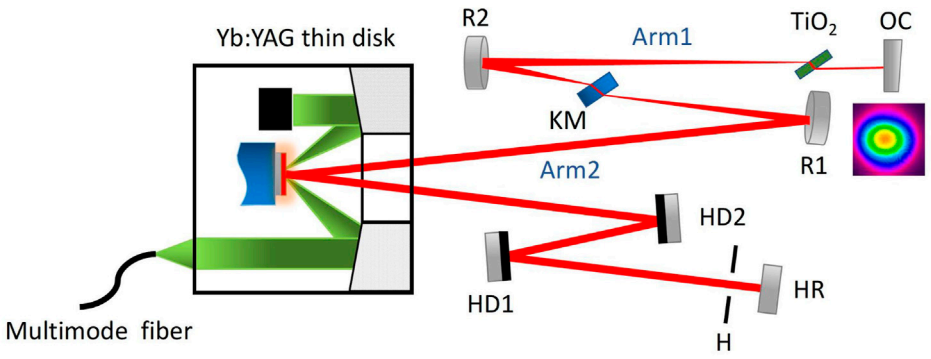

FIGURE 1
Schematic of the Yb:YAG thin-disk oscillator. The Yb:YAG thin disk is wedged with a ROC of −20 m. HR, high-reflection mirror; HD, high-dispersion mirrors; OC, output coupler; KM, Kerr medium (sapphire plate); H, hard aperture; R1 and R2, concave mirrors with ROC of −150 and −50 mm, respectively.

progress has been made in promoting one or two of those three aspects [11–16], However, it is rather difficult to combine all these desired properties within one oscillator, limited by several reasons such as thermal effects of the bulk crystals, the narrow bandwidth of the gain medium and the mode locking condition and so on.

Compared to the fiber and bulk-crystal mode-locked oscillators, thin-disk technology has shown great advantage in scaling the average power and pulse energy since its invention in 1994 [17]. Pulses with average powers of several hundreds of watts and pulse energies of several tens of microjoules have been achieved directly from the Yb:YAG thin-disk oscillators with either Kerr lens mode locking (KLM) or semiconductor saturable absorber mirrors (SESAM) [18–21]. Based on the scheme of strong self-phase modulation, the pulses delivered from Yb:YAG thin-disk oscillators can be shortened with pulse durations down to ~50 fs while maintaining a high average power level [22, 23]. To obtain short-duration pulses from a thin-disk oscillator, new materials with broader spectrum bandwidth than Yb:YAG were also used as thin-disk gain media such as Yb:Lu_2O_3, Yb:$LuScO_3$ and Yb:CALGO [24–26], resulting in the generation of sub 100-fs pulses with average powers up to tens of watts. In addition, with Ho:YAG thin disks, passive mode locking at the wavelength of 2.1 μm was realized first by KLM and then followed by SESAM mode locking, which delivered femtosecond pulses with average powers of about several tens of watts [27–29].

In terms of repetition rate, most of the thin-disk oscillators operated at a repetition rate below 100 MHz due to the conflicting requirements between the short cavity length and the large laser beam size. One solution is to generate mode-locked pulses inside a ring cavity, however, it still confronts the same problem mentioned above when further increase of the repetition rate up to more than 200 MHz is required. Another solution utilized asymmetric cavity configuration through two concave mirrors with different radii of curvature (ROC) in a standing-wave cavity, which reconciled the inconvenience of arrangement due to the short cavity length and the large beam size on the thin disk. This scheme has resulted in pulses generation with pulse duration around 250 fs and average powers of 75 W at a repetition rate up to 200 and 260 MHz from Yb:YAG thin-disk oscillators [30], showing great potential in generating high-repetition-rate, high-power frequency combs. Based on these results, a new scheme named distributed kerr-lens mode locking (DKLM) was invented to enhance the Kerr-lens effect, which greatly broadened the output spectrum of the Yb:YAG thin-disk oscillators and shortened the pulse duration down to sub 50 fs [31]. However, the average power was limited to around 4 W, partly because of the high reflection loss from the surfaces of multiple nonlinear Kerr plates. In this work, we optimize the DKLM scheme by replacing the separate Kerr plates with a single plate possessing high nonlinear coefficient. This significantly decreases the cavity loss and results in a combination of a high repetition rate (>200 MHz), high average power (~10 W) and short pulse duration (~50 fs) within one oscillator.

Experimental setup

The experimental setup is shown in Figure 1. The Yb:YAG thin disk is ~100 μm thick and placed inside a 36-pass pump module used as one of the folding mirrors in a Z-shaped cavity. It is pumped by a fiber-coupled diode laser at 940 nm with a pump beam size on the disk of 2.5 mm in diameter. We designed and built the cavity with a telescope section consisting of two concave mirrors with different radii of curvature (150 and 50 mm). This asymmetric configuration enables a larger mode size in the cavity arm containing the Yb:YAG disk (Arm 2). The dispersive mirrors are also placed in

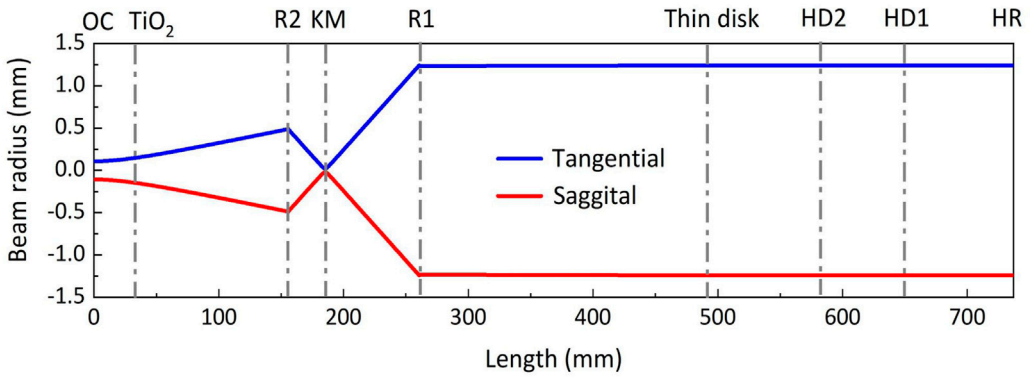

FIGURE 2
Intracavity mode distribution of the 203-MHz Yb:YAG thin-disk oscillator.

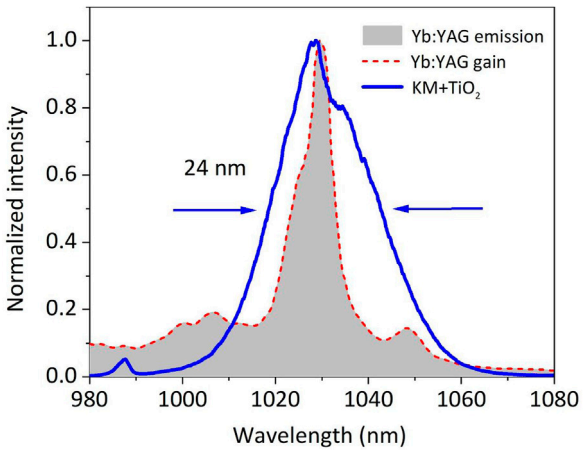

FIGURE 3
Comparison of the output spectrum, the emission spectrum and the gain spectrum of Yb:YAG.

this arm in order to avoid damage caused by the high intensities during the mode locking start-up. In contrast, the other arm (Arm 1) has a much smaller beam size with a diameter on the OC of 160 μm. The intracavity mode distribution is illustrated in Figure 2. It can be found that the beam is well collimated in Arm 2, indicating an almost same beam size (2.2 mm) on the end HR mirror and the disk. The whole cavity length was around 740 mm, corresponding to a repetition rate of 203 MHz. A 2-mm thick sapphire plate is placed in the focus of the telescope section as the Kerr medium, which provides the necessary self-focusing effect and self-amplitude modulation assisted with a hard aperture for the initiation of the Kerr lens mode locking. To enhance the Kerr-lens effect, a piece of TiO_2 crystal is inserted in the Arm 1 at the Brewster angle close to the OC. A pair of high-dispersion mirrors were used to provide a negative round-trip group-delay-dispersion of −2000 fs^2.

Results and discussion

The experiment was carried out based on the DKLM concept, similar to that reported in our previous work [31]. In that work, we increased the overall modulation depth for the passive mode locker and enhanced the Kerr lens effect by distributing various Kerr lenses at proper locations inside the oscillator cavity. As a result, the output pulse durations from an Yb:YAG thin-disk oscillator were well below what the emission bandwidth limit (FWHM) of the gain medium can support. However, the decreased optical-to-optical efficiencies and average powers with more crystals inserted are related to the significant losses induced by the multiple Kerr plates. Since there were six uncoated plates inserted in the beam path (excluding the KM), the losses resulted from absorption and surface reflection cannot be ignored. The most direct way of decreasing these losses is to use single crystal instead of a group of them, and the total nonlinearity provided by single crystal and by a set of crystals should be equal. Therefore in this work, we optimized the DKLM scheme with this idea and chose a 0.5-mm thick TiO_2 crystal (with the nonlinear refractive index of $\approx 5.6 \times 10^{-15}$ cm^2/W) which had a similar nonlinearity as the group of six Kerr plates (15-mm thick sapphire crystals with $n_2 \approx 1.3 \times 10^{-16}$ cm^2/W and 3-mm thick YAG crystal with $n_2 \approx 2.7 \times 10^{-16}$ cm^2/W) [32]. As a consequence, the output coupling ratio under the condition of the same intracavity additional nonlinearity could be increased from 3% to 5% due to the decreased losses. The mode locking was realized under a pump power of 180 W, and 55-fs pulses with an average power of 9.4 W could be obtained. The optical-to-optical efficiency is calculated as 5.2%, which is

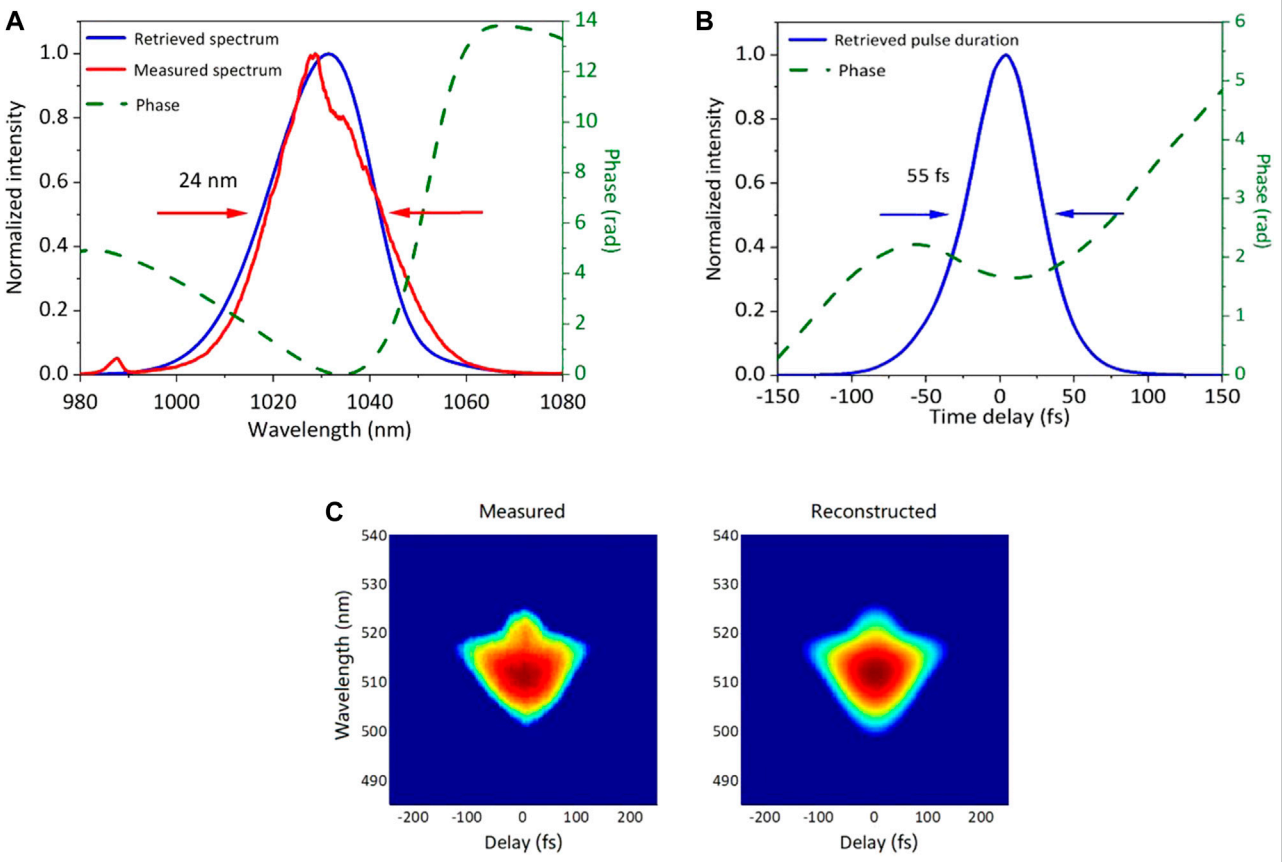

FIGURE 4
Characteristics of the output pulses. **(A)** Measured and retrieved spectra of the pulses. The measured spectrum extends from 980 to 1,080 nm. **(B)** Retrieved temporal intensity showing a pulse duration of 55 fs. **(C)** The comparison of the measured and retrieved FROG traces.

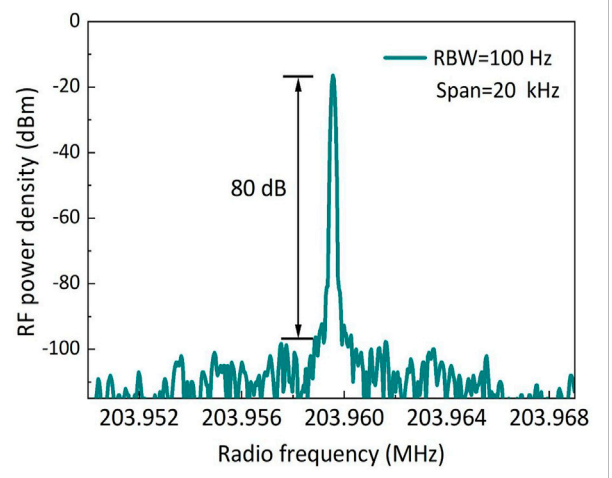

FIGURE 5
Fundamental RF spectrum measured at a resolution bandwidth of 100 Hz showing a signal-to-noise ratio of 80 dB.

approximately 50% higher than the configuration with six plates in our previous work.

The measured spectrum was shown in Figure 3 (OSA, Ando AQ-6315A), which spans from 980 nm to 1,070 nm with a width of 24 nm at full width at half-maximum (FWHM). This is 2.5 times wider than the emission bandwidth of the Yb:YAG crystal (9 nm at FWHM). The small peak around 990 nm is speculated to come from the change of the dispersion from the HD mirrors. We used a home-built frequency-resolved optical gating (FROG) apparatus to further characterize the spectrum and the pulse duration of the output pulses, as shown in Figure 4. The retrieved temporal intensity shows a pulse duration of 55 fs. Figure 4C shows a good matching between the measured and the retrieved FROG traces, indicating that our retrieval is reliable. The repetition frequency of the oscillator was characterized with a radio frequency (RF) spectrum analyzer, as illustrated in Figure 5. It shows a high signal-to-noise ratio of 80 dB at a resolution bandwidth of 100 Hz (Agilent, E4447A), implying a stable mode-locked operation of the thin-disk oscillator. Once

started, the KLM operation could be maintained for several hours under ambient air conditions. Stable operation for a whole day will be expected with a professionally designed housing. The output pulses have an excellent beam profile with the beam quality factor M^2 less than 1.1 (Figure 1).

For the next step, the improvement could be implemented by building a resonator with even stronger asymmetry, which will help to both enlarge the beam size on the thin disk for higher gain and higher output power and increase the repetition rate while preserving a large pump beam size on the disk. A single-pass configuration with the thin disk placed as an end mirror and a replacement of the concave mirrors by lenses are also beneficial for the cavity arrangement of higher repetition rate. Besides, the current TiO_2 crystal is slightly wedged, resulting in residual reflection losses which can be reduced in the future. Higher output power could be expected with a plane-parallel crystal. To further shorten the pulse duration, a thicker TiO_2 plate or a plate with higher nonlinear coefficient could be used to further enhance the Kerr lens effect. New thin-disk materials with broader emission spectrum bandwidth such as Yb:Lu_2O_3 or Yb:CALGO could also be applied with the same method, and new record of the pulse duration would be expected.

Conclusion

In conclusion, we have demonstrated a DKLM Yb:YAG thin-disk oscillator with a single TiO_2 plate as the additional Kerr lens. This configuration enhanced the Kerr lens effect while greatly reducing the reflection losses inside the cavity, which enabled a higher output average power and optical-to-optical efficiency compared to our previous report. As a result, 9.4-W pulses with pulse duration of 55 fs at a repetition rate of 203 MHz were generated. Further improvement to the repetition rate, average power and pulse duration will be expected with stronger cavity asymmetry, new thin-disk materials and higher intracavity nonlinearity. The current oscillator combines a high repetition rate (>200 MHz), a high average power (~10 W) and short pulse duration (~50 fs) within one resonator, which provides a reliable laser source for the generation of high power optical frequency comb in the near infrared and even mid-infrared region.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

The main setup was designed and built by JZ. The data was measured, analyzed and interpreted by HL, TY, JX, QW, HX, and JZ. The experiment was conceived by JZ. All authors reviewed and contributed to the final manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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