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Diode-pumped 13 W Yb:KGW femtosecond laser

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We report on a high-power diode-pumped Yb:KG$(WO_4)_2$ (Yb:KGW) mode-locked laser with a semiconductor saturable absorber mirror (SESAM). For 32.7 W of incident pump power, we generate 261 fs pulses with the maximum average output power of up to 13.0 W and spectrum centered around 1039 nm at 68.4 MHz, corresponding to 190 nJ of single pulse energy and 0.72 MW of peak power. The optical-to-optical conversion efficiency is 39.8%, and the slope efficiency is 64.4%. The Yb:KGW laser exhibits a power stability better than 0.543% of the root-mean-square in 2 h.

Keywords: ultrafast laser; high-power femtosecond laser; Yb:KGW crystal; semiconductor saturable absorber mirror.

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1. Introduction

In recent years, more efforts have been devoted to the research of ultrashort pulses with high average power for various applications such as pumping of optical parametric oscillators, material micromachining, multi-photon imaging, and terahertz applications[1–3]. At present, the Ti:sapphire laser is limited to output power below 4 W due to the lower pump power and the quantum efficiency of the crystal. In addition, its pump source is quite expensive. In contrast, the Yb^{3+}-doped femtosecond laser has more great potential because it can be pumped by tens or even hundreds of watts laser diodes (LDs), and the center wavelength ranges from 0.9 μm to 1.1 μm. Despite there being many reports on Yb-doped lasers, the trade-off between the average power and pulse duration was still a challenging topic. Therefore, it is very crucial to choose a novel gain medium to meet a wide spectrum supporting the generation of shorter pulses and good thermo-mechanical properties allowing for high-power laser pumping.

So far, many Yb-doped gain media, such as Yb:CaF_2, Yb:$Y_3Al_5O_{12}$ (Yb:YAG), Yb:$Ca_4(Gd,Y)O(BO_3)_3$ (Yb:GdYCOB), Yb:$KY(WO_4)_2$ (Yb:KYW), Yb:$KG(WO_4)_2$ (Yb:KGW), Yb:$CaGdAlO_4$ (Yb:CALGO), and Yb:$CaYAlO_4$ (Yb:CALYO), have proved to be suitable for mode-locked lasers and exhibited good laser performance[4–10]. Among these crystals, the Yb:KGW, Yb:CALGO, and Yb:CALYO crystals have the most potential as gain media, which are suitable for generating high-power lasers with short pulse duration[11–15]. Using a Yb:CALGO crystal, 96 fs pulses were obtained with average power of 12.5 W, which is the highest output power from sub-100-fs Yb-doped oscillators[9]. In 2021, a Yb:CALGO oscillator delivering 17.8 fs pulses with 26 mW of average power was reported[16]. Moreover, Tian *et al*. of Xidian University reported on the 98 fs Yb:CALYO oscillator with 10 W of average output power at 81 MHz based on Kerr-lens mode-locking[17]. Also, much research is focused on the Yb:KGW crystal, which offers wide emission spectrum across 1023 nm–1060 nm and high thermal conductivity with $3.3\ \mathrm{W\cdot m^{-1}\cdot K^{-1}}$ [18].

At present, the most common methods to obtain ultrafast lasers are the Kerr-lens and semiconductor saturable absorber mirror (SESAM) mode-locking for Yb-doped oscillators. Kerr-lens mode-locking is usually accompanied by other effects such as self-phase modulation, which can increase new spectral components to support shorter pulse duration. In 2017, the Kerr-lens mode-locked Yb:KGW laser generated 120 fs pulses at 1.2 W and 240 fs pulses with the maximum average output power of 2.3 W due to the limitation of the strong continuous wave (CW) spectrum components[7]. Later, the Yb:KGW oscillator generated 78 fs pulses with 0.65 MW of peak power and 50 nJ of single pulse energy at the repetition rate of 36 MHz[19]. In 2019, Meng *et al*. reported 73 fs pulses with 4 W at the repetition frequency of 75.5 MHz[20]. Furthermore, a Kerr-lens mode-locking initiated with a SESAM Yb:KGW laser delivered 67 fs pulses with 3 W of average output power[21]. Recently, pulses as short as 56 fs were demonstrated at an average power of 1.95 W, which is the shortest pulse duration from a Yb:KGW laser[22]. However, the reports mentioned above indicated that increasing output power to 10 W is challenging with Kerr-lens mode-locking due to small spot size on a crystal. In contrast, pure SESAM mode-locking has more potential in scaling output power due to flexible parameters, such as modulation depth, saturation energy density, and others. The most noteworthy advantage is that it has high stability and self-start capability. Moreover, the cavity adjustment makes it simple to obtain a high-power laser with suitable power density on the SESAM. In 2000, Brunner *et al.* reported the first, to the best of our knowledge, SESAM mode-locked Yb:KGW laser, where 176 fs pulses with an average power of 1.1 W were obtained[23]. Then, 100 fs pulses have been demonstrated with 126 mW of output power based on the Yb:KGW crystal[24]. Furthermore, the Yb:KGW oscillator generated 350 fs pulses with 2.4 W of output power[14]. In 2008, Calendron of high-Q laser production Gmbh *et al.* demonstrated 24 W CW laser using the dual Yb:KYW crystals and two LDs. Using SESAM, an average output power of 17 W was obtained in the positive dispersion regime. The pulse duration was around 450 fs[25]. Compared to the single crystal, dual crystals can make the small signal gain larger and improve the optical-to-optical conversion efficiency. However, this makes the resonator design complicated and adds the cost of the laser system. In 2015, Kisel *et al.* demonstrated a diode-pumped SESAM mode-locked Yb:KGW laser, where the average output power was 8.8 W, and the pulse duration was 162 fs[26]. In 2019, we demonstrated a diode-pumped SESAM mode-locked Yb:KGW oscillator, which delivered 160 fs pulse with 7.6 W of average output power[21]. The Yb:KGW crystal can be used not only to generate high-power laser but also to obtain large energy laser[27,28]. In 2020, the Yb:KGW regenerative amplifier delivering 227 fs pulses with single pulse energy of 1.2 mJ at the repetition frequency of 1 kHz after compression was reported[28]. Thus, it can be seen that the higher average power is usually achieved at the cost of a longer pulse.

In this work, the single LD was used as the pump source, and one Yb:KGW crystal was used as the gain medium. We demonstrate a high-power, SESAM mode-locked Yb:KGW oscillator delivering 261 fs pulses with 13.0 W of average output power at the repetition rate of 68.4 MHz, corresponding to 190 nJ of single pulse energy and 0.72 MW of peak power. The power stability root-mean-square (RMS) for 2 h was less than 0.543%, and the laser exhibited a high beam quality.

2. Experiments

The schematic experimental configuration of the SESAM mode-locked Yb:KGW laser is shown in Fig. 1. An unpolarized multimode fiber coupled LD with 105 μm of fiber core diameter and 0.22 of numerical aperture was used as pump source, where its emission wavelength was 980 nm, and the maximum output power was 50 W. An Nm-cut 3%-doped Yb:KGW crystal (CASTECH, China) was used as gain material, and its size

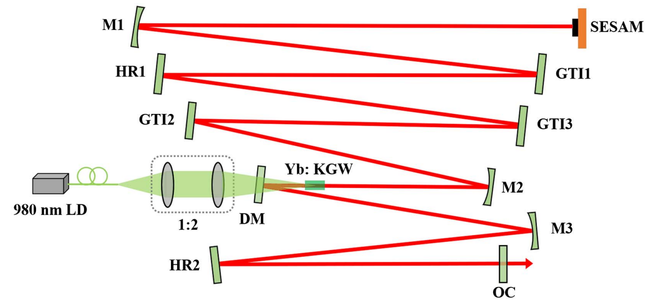

Fig. 1. Experimental configuration of the SESAM mode-locked Yb:KGW laser. LD, laser diode; Yb:KGW, Yb:KG$(WO_4)_2$; SESAM, semiconductor saturable absorber mirror; DM, dichroic mirror; HR, high reflection mirror; M1, M2, M3, concave mirrors (R = 500 mm, 300 mm, 500 mm, respectively); OC, output coupler; GTI, Gires–Tournois interferometer mirror.

was 5 mm (length) × 3 mm (width) × 3 mm (height). In addition, the crystal was antireflection-coated around 980 nm–1100 nm. In order to reduce the heat accumulated inside the crystal with high-power pumping, the crystal was mounted on a copper sink and cooled to 14°C. The crystal has a single pass pump absorption rate of 70%–80%, depending on the pump power. The pump laser was focused into the crystal by a coupling system with a magnification of 2.0. The waist radius was 100 μm in the center of the Yb:KGW crystal. In order to obtain Fourier limited pulse width, we used three Gires–Tournois interferometer mirrors (GTI1, GTI2, and GTI3) to control intracavity dispersion, with a total group velocity dispersion (GVD) of -5800 fs^2. The "DM" was a dichroic mirror coated for high reflection (HR) across 1030–1200 nm and high transmission (HT) across 820–990 nm. The "M1," "M2," and "M3" represent the concave mirrors coated for HR ($R > 99.9\%$) across 1000–1065 nm, and the radius of curvature was 500 mm, 300 mm, and 500 mm, respectively. Both "HR1" and "HR2" were plane mirrors with fused silica substrates coated for HR in the range of 1000–1065 nm. The output coupler (OC) mirror with a transmittance of 10% was used in the resonator. All of the laser-coated cavity mirrors used in the experiment, including the HR mirrors, DMs, and OCs (Layertec GmbH, Germany), were designed to have lower dispersion and higher reflectivity to obtain short pulse duration and reduce transmission loss. In order to obtain soliton mode-locking, the SESAM with high optical quality was inserted into the cavity to initiate and maintain mode-locking. As a semiconductor material, the SESAM is vulnerable to heat damage. Therefore, it was mounted on a water-cooled copper heat sink and cooled to 14°C. The parameters of the SESAM were as follows: modulation depth of 2.4%, relaxation time of 1 ps, and saturation fluence of $F_{sat} = 70\,\mu J/cm^2$ at the center of 1064 nm. The SESAM was placed on the translation stages to control the distance between the SESAM and M1. The distance determines the cavity mode size and power density on SESAM and has effects on scaling the output power and the mode-locking stability. Both M2 and M3 were also fixed on the precise translation stages to control the spot distribution in the resonator and optimize the mode matching between the pump and the laser. The length of the resonator is 2174 mm, corresponding to the repetition frequency of 69 MHz.

3. Results and Discussion

In this experiment, we obtained the CW mode-locked laser using the SESAM as an end mirror to initiate and maintain the mode-locking. Firstly, with 8% transmittance output couple mirror and GTI mirrors of a total GVD of $-4800\,\mathrm{fs}^2$, we obtained 196 fs pulses with 8.3 W of average output power. We focus on scaling output power, so the lower transmission OCs were not used. Then, using the 10% transmission output couple mirror, we measured the average output power, pulse duration, spectral bandwidth, radio frequency (RF) spectrum, beam quality factor, and so on. In a linear cavity, the relationship between output power and pump power was measured, as shown in Fig. 2(a). It was seen that the output power suddenly increases faster at the pump power of 12.5 W. It means that the pump power threshold of the mode-locked state was 12.5 W. With the pump power of 32.7 W, the maximum average output power operating in the SESAM mode-locked regime was 13 W, corresponding to a slope efficiency of 64.4% and the optical-to-optical conversion efficiency of 39.8%. Compared to 15.0 W of CW power, the output power operating in the mode-locking region dropped mainly due to the transmission loss introduced by GTI mirrors and the unsaturated loss of the SESAM. It is worth mentioning that the appropriate distance between the SESAM and M1 concave mirror is vital to scale the output power. When the distance was between 252 mm and 258 mm, the mode-locked laser ran in a good state. The spot radius on the SESAM was 180 μm in this experiment. Figure 2(b) shows the

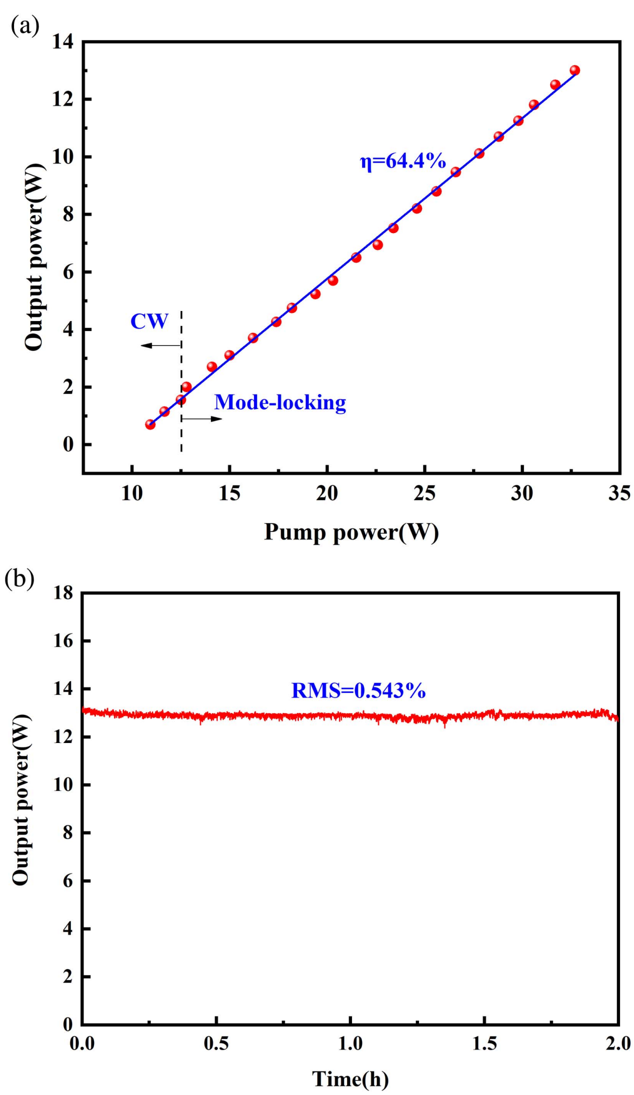

Fig. 2. (a) Output power as a function of the pump power. The blue solid line has a slope efficiency of 64.4%. (b) Power fluctuations at 13 W average output power in 2 h.

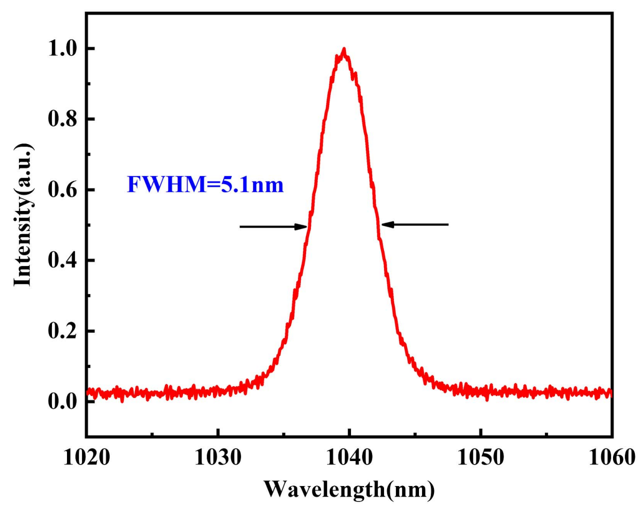

Fig. 3. Spectral distribution of Yb:KGW mode-locked laser at the average output power of 13 W.

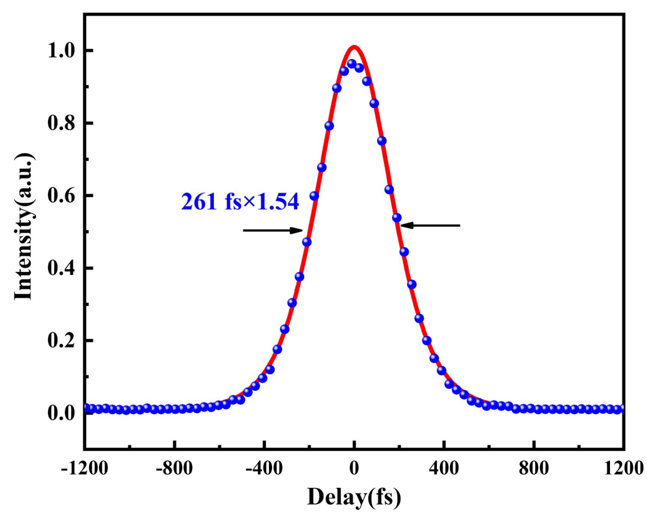

Fig. 4. Measured intensity autocorrelation trace of Yb:KGW femtosecond laser at the central wavelength of 1039 nm.

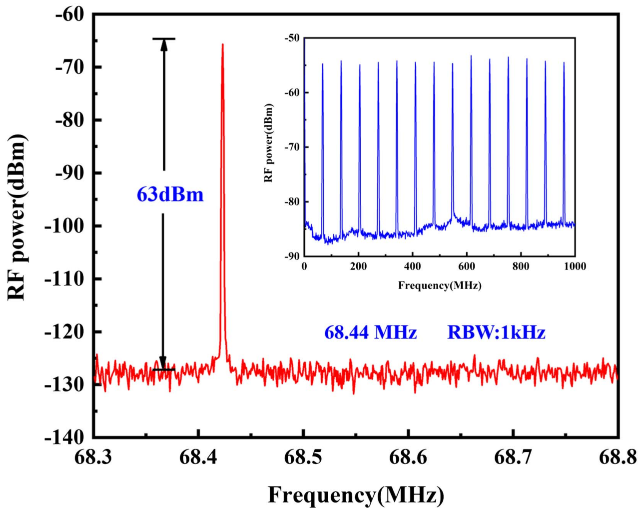

Fig. 5. Typical RF with an RBW of 1 kHz. Inset: RF spectrum at 1 GHz wide span with the RBW of 200 kHz.

power fluctuations at 13 W of average power, and the RMS stability was about 0.543% in 2 h; this exhibited the high performance of the Yb:KGW laser. When the pump power was greater than 32.7 W, both the SESAM and the gain crystal were easily damaged. Even if given perturbation, the mode-locking still cannot start again.

As released in Fig. 3, the optical spectrum was measured by an optical spectrum analyzer (OSA, Yokogawa AQ6370C) and centered at 1039 nm with a full width at half-maximum (FWHM) spectral bandwidth of 5.1 nm, corresponding to 222 fs of Fourier limited pulse duration. With a total negative group delay dispersion (GDD) of 5800 fs^2, as short as 261 fs pulses assuming $sech^2$ fitting were obtained at maximum output power of 13 W, as shown in Fig. 4.

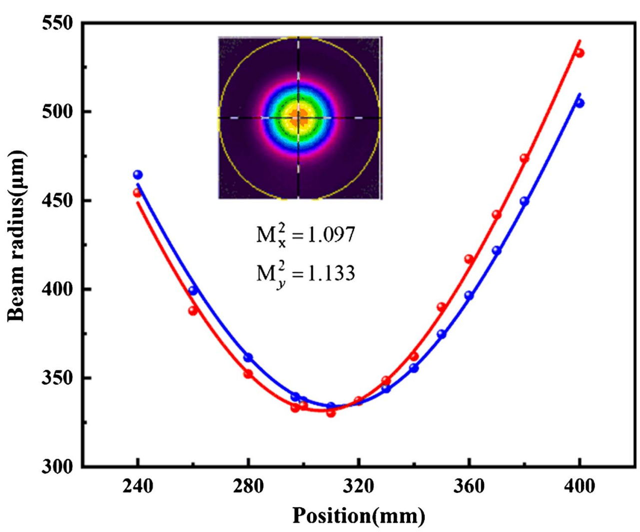

Fig. 6. Measured beam quality factor M^2 of Yb:KGW femtosecond oscillator at the 13 W average output power.

As can be seen from the RF spectrum with a resolution bandwidth (RBW) of 1 kHz displayed in Fig. 5, the fundamental tone at 68.44 MHz measured by an RF spectrum analyzer (E4402B, Agilent) was more than 63 dB above the noise floor. With an RBW of 200 kHz, an inset in Fig. 5 shows that no additional peaks between the higher-order modes were observed. The beam quality factors were measured by a commercial M^2 factor meter (Spiricon M^2-200s), as described in Fig. 6. At 13 W of maximum output power, the beam quality factors were $M_x^2 = 1.097$ and $M_y^2 = 1.133$ in the horizontal and vertical directions, respectively. These indicated that the mode-locking oscillator exhibited a high laser performance.

4. Conclusion

In conclusion, we have reported on a high-power diode-pumped SESAM mode-locked Yb:KGW laser. With the 10% transmission OC, the maximum average output power directly generated from the oscillator was up to 13.0 W, corresponding to the optical-to-optical conversion efficiency of 39.8%. When the total GVD was $-5800\ fs^2$, the oscillator delivered 261 fs pulses centered around 1039 nm with peak power of 0.72 MW and per pulse energy of 190 nJ at a repetition rate of 68.4 MHz.

In order to scale the output power while persisting short pulse duration in the SESAM mode-locked regime, some improvements as follows could be made. Firstly, increasing the radius of the spot on the crystal can improve the utilization rate of the pump laser and allow high-power laser pumping. Meanwhile, the thin fused quartz is inserted into the resonator to introduce self-phase modulation resulting in a broader spectrum, and more precise dispersion is also necessary to obtain shorter pulse duration. Finally, the SESAM with high optical quality and high damage threshold is used to optimize the output laser parameters. This will be a potential laser source in various applications.

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