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Sub-100 fs watt-level Kerr-lens mode-locked Yb:CaYAlO$_4$ laser with a gigahertz repetition rate

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We report a 1.04 GHz high-power Kerr-lens mode-locked Yb:CaYAlO$_4$ laser pumped by a single-mode fiber laser at 976 nm. Based on a bow-tie cavity, stable unidirectional mode-locked operation is obtained with an output coupler of 1.6%. The oscillator delivers pulses with an average power of 1.46 W and with the pulse duration of 99 fs, which, to the best of our knowledge, is the first gigahertz-level Kerr-lens mode-locked laser based on the Yb:CaYAlO$_4$ gain medium. We believe that the watt-level solid-state femtosecond laser at GHz would be an excellent source for developing time-resolved broadband dual-comb spectroscopy.

KEYWORDS

ultrafast Laser, optical frequency comb, Kerr-lens mode-locked, all-solid-state-laser, Yb:CYA

1 Introduction

Femtosecond optical frequency combs (OFCs) with high repetition rate and high average power are becoming desirable with the emerge of new application requirements, such as microwave photonics, Terahertz generation, analog-to digital conversion, bio-optical imaging, astronomical calibration, to name a few [1–5]. Especially for the time-resolved broadband dual-comb spectroscopy (DCS), the repetition rate and the average output power are two of the most important factors for the following reasons [6–8]. Firstly, according to the Nyquist condition, the obtainable spectral bandwidth of DCS satisfies $\Delta\nu \leq \frac{f_{rep}^{\ 2}}{2\Delta f_{rep}}$. For a given Δf_{rep}, higher repetition rate leads to a wider optical spectral bandwidth. Secondly, since the acquisition time for a single-shot, full optical spectrum is defined as $t_{sample} = \frac{1}{\Delta f_{rep}}$, trade-offs have to be made between f_{rep} and Δf_{rep} in favor of broad bandwidth and fast sampling speed, which is easier for gigahertz-level repetition rate than MHz-level. The third important parameter of DCS is the signal to noise ratio (SNR), and it is proportional to the power of individual comb line, which increases with the repetition rate and the average output power for a given optical bandwidth. Although higher repetition rate is more favorable for the above-mentioned parameters, the expense is the decreased spectral resolution. Simulations indicate that 1-2 GHz repetition rate could balance sufficient sampling rate to resolve absorption lines of gases with all pressures and maintain fast acquisition speed at the meantime [9]. Finally, most of the molecular fingerprints lie in the range of near-infrared and mid-infrared, which is difficult to directly access for most of the gain medium. Non-linear parametric conversion becomes an effective method to broad the spectrum from ultraviolet to mid-infrared, which makes the high average output power of the femtosecond OFC source an necessitate [10, 11].

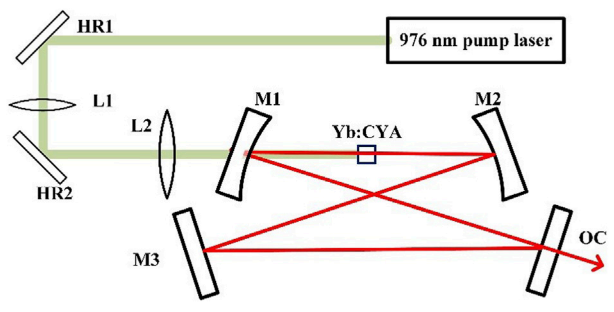

FIGURE 1
Schematic of the optical setup.

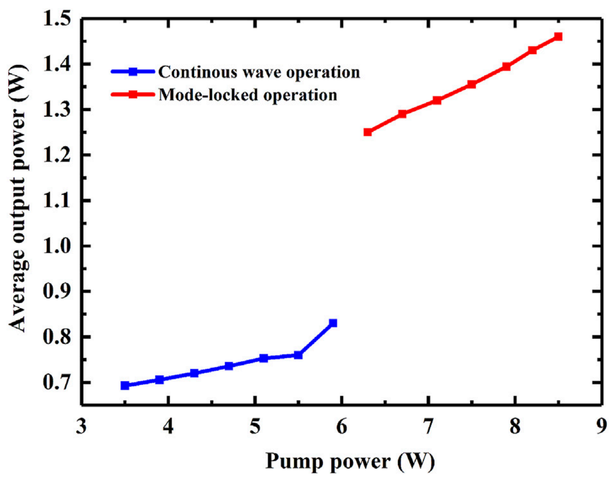

FIGURE 2
The output power varies with pump power.

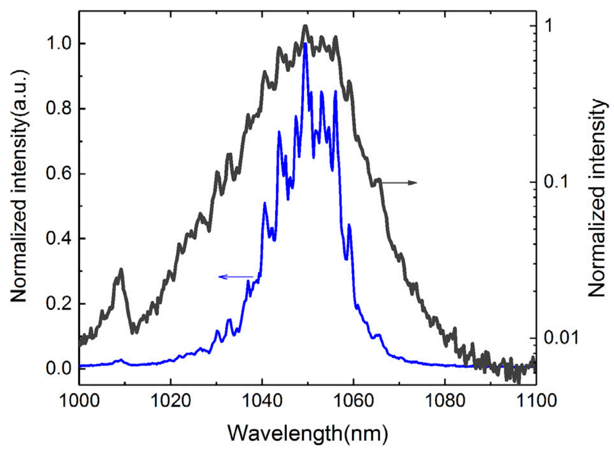

FIGURE 3
The output optical spectrum of the mode locked laser.

There are several approaches to generate high repetition rate femtosecond lasers. Electro-optical frequency comb could access >10 GHz regime, but it is challenging to achieve power scaling and self-referenced frequency locking, which is the same as the microcomb [12–14]. Femtosecond mode-locked lasers can be ideal candidates for developing <10 GHz OFCs. Compared to fiber mode-locked lasers as well as semiconductor lasers, all-solid-state femtosecond mode-locked lasers have the advantages of flexible cavity alignment, high average output power as well as the intrinsic low-noise performances [15]. Several significant results delivering gigahertz repetition rate ultrafast pulses based on the Ytterbium (Yb) doped gain medium around 1 μm have been reported in the last decade, because of the low-cost pump, low quantum loss and high optical to optical efficiency. In 2012, S. Pekarek et al. reported a saturable absorber mirror (SESAM) assisted mode-locked Yb:KGW laser with a repetition rate of 4.8 GHz, delivering the average power of 1.9 W with the pulse duration of 396 fs [16]. In 2013, A. Klenner et al. demonstrated self-referenced carrier envelope phase offset (CEO) detection based a 1.06 GHz SESAM mode-locked Yb:KGW laser with a pulse duration of 125 fs at an average power of 3.4 W [17]. In 2017, S. Hakobyan et al. obtained a diode pumped GHz SESAM mode-locked Yb:CALGO laser with an average power of 2.1 W and a pulse duration of 96 fs, and demonstrated self-referenced full stabilization [18]. In 2017, A. S. Mayer et al. presented a 10.6 GHz SESAM-assisted soliton mode-locking Yb:CALGO laser with a self-defocusing straight-cavity design, delivering 166 fs pulses at an average power of 1.2 W [19].

Compared to the SESAM mode-locking, the Kerr-lens mode-locked (KLM) mechanism based on self-focusing principle is much more beneficial for sub-100 fs ultrashort pulse generation and could access higher repetition rate with more flexible cavity alignment. In 2012, M. Endo et al. developed a diode-pumped 4.6 GHz repetition-rate Yb:KYW KLM laser with an output power of 14.6 mW and a pulse duration of 146 fs [20]. In 2013, M. Endo et al. reported a 6 GHz KLM Yb:Lu_2O_3 ceramic laser with an average power of 10 mW [21]. They further developed a direct 15 GHz optical frequency comb based on the KLM Yb:Y_2O_3 ceramic laser with an average power of 60 mW in 2015 [22]. In 2019, S. Kimura presented a compact KLM Yb:Y_2O_3 laser with a only three-element setup, delivering pulses with a repletion rate of 23.8 GHz and a pulse duration of 120 fs at the average power of 20 mW [23]. Although the reported KLM femtosecond laser have broken through 20 GHz repetition rate, the output powers are limited to 100-mW level.

In this paper, we present a gigahertz watt-level KLM Yb:$CaYAlO_4$ (Yb:CYA) laser with sub-100 fs pulse duration. A 976 nm single-frequency fiber laser with high brightness and good beam quality was employed as the pump. The Yb:CYA crystal is chosen as the gain medium, since it exhibits good performances in wide spectral emission, thermal conductivity as well as other optical and mechanical properties [24]. W. Tian et al. have achieved 10.4 W KLM Yb:CYA laser delivering sub-100 fs pulses with the peak power of 1.14 MW [25]. Up to now, results have been only limited to 100 MHz repetition rate regime. Here based on the Yb:CYA laser medium, we developed the KLM oscillator, delivering pulses with a repetition rate of 1.04 GHz, a pulse duration of 99 fs at an average power of 1.46 W. It is, to the best of our knowledge, the first watt-level KLM Yb:CYA femtosecond laser at gigahertz repetition rate, which would be a potential source for the time-resolved dual comb spectroscopy.

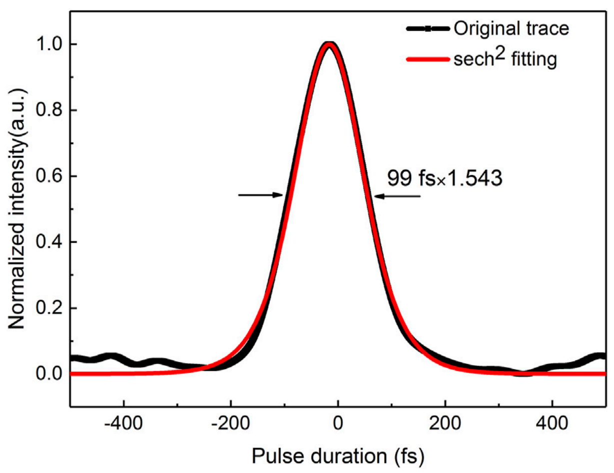

FIGURE 4
The measured autocorrelation and the sech^2 fitting curve of the output pulse.

2 Experimental setup

The pump laser is an Ytterbium doped single-frequency fiber laser with high brightness, which is an ideal laser source for pumping high repetition rate femtosecond KLM laser. The used fiber laser delivers an average power of up to 8.5 W at the wavelength of 976 nm. The pump light is firstly collimated by a lens with a focal length of 300 mm and then focused by a lens with a focal length of 50 mm. A tight focus is used to enhance the Kerr effect and the focal spot size at the center of the crystal is measured to be 43 × 39 μm^2. The focused power density could reach 5.85 × 10^5 W/cm^2, which avoids the Q-switched instabilities to some extent.

The gain medium was an a-cut 3 mm-thick Yb:CYA crystal with a doping concentration of 8 at%, which is mounted on a water-cooled copper heat sink with the temperature of 13°C. The gain crystal is coated with anti-reflection in the range of 900 nm–1200 nm on both sides. The broad and flat emission cross section of the Yb:CYA gain crystal is ideal for generating sub-100 fs ultrashort laser pulses.

The laser setup is based on a bow-tie cavity, as shown in Figure 1. The radius of curvature of the two concave mirrors M1 and M2 are 50 mm. One concave mirror M1 serves as the pump mirror with a high transmission of the 976 nm pump wavelength and high reflection of the oscillating wavelengths centered at 1048 nm. Since the limited cavity elements makes it difficult for dispersion compensation, the other concave mirror M2 is chosen to be a Gires-Tournois interferometer (GTI) mirror providing a group delay dispersion of −550 fs^2. The flat mirror M3 is also a GTI mirror with the group delay dispersion of −800 fs^2. An output coupler with the transmission of 1.6% is selected to extract the pulse energy. The four-mirror ring cavity is designed with the length of 288 mm, corresponding to a repetition rate of 1.04 GHz. According to the ABCD matrix, the beam diameter of the intracavity laser mode in center of the crystal is about 46 μm, which is slightly bigger than the pump spot and is suitable for the Kerr-lens mode locking.

3 Results and discussion

The cavity is properly aligned at first and stable continuous wave operation is obtained in two directions with the total power of 1.6 W. To achieve Kerr-lens mode-locking, the position of the concave mirror M2 is scanned across the stability region. When the concave mirror M2 arrived the inner edge of the stability region, the output power becomes unstable and mode-locking could be achieved with fine tuning of the concave mirror M2. Once the Kerr-lens mode-locking is initiated, the output power jumped to 1.2 W and the output spectrum is broadened. The Figure 2 Shows that the output power of the Yb:CYA laser varies with the pump power and the pumping threshold for Kerr-lens mode-locking is measured to be 6.3 W. As the pump power increases to maximum of 8.5 W, the Kerr lens mode-locked pulses with an output power up to 1.46 W was obtained. Besides, it can be seen from the change trend of the mode-locked operation curve in Figure 2 that there is still room for improving the output power.

The output optical spectrum is measured by an optical spectrum analyzer, as shown in Figure 3. The full width at half maximum (FWHM) of the spectrum is 20 nm centered at 1048 nm, which

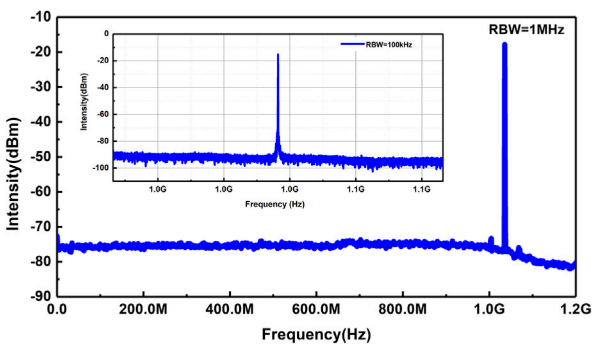

FIGURE 5
Radio frequency spectrum of the laser with the resolution bandwidth (RBW) of 1 MHz and 100 kHz (inset).

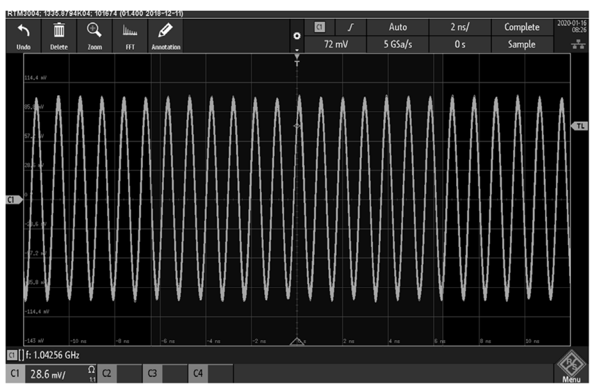

FIGURE 6
The temporal trace of the pulse sequences.

corresponds to a Fourier transform-limited pulse duration of 54 fs. The pulse duration is measured by using a commercial autocorrelator (APE PulseCheck). As shown in Figure 4, The $sech^2$-fit pulse duration is 99 fs. The single-pulse operation is not only verified by the autocorrelation trace but also by the microwave frequency spectrum and the temporal trace recorded by the oscilloscope.

Figure 5 shows the radio frequency spectrum of the repetition rate, which is recorded by a photodetector and measured by an RF spectrum analyzer (Rohde & Schwarz FSW 26). Under the resolution bandwidth (RBW) of 1 MHz and the frequency span of 1.2 GHz, the SNR is about 60 dB. Under the RBW of 100 kHz and the frequency span of 100 MHz, the SNR is about 80 dB, as shown by the inset of Figures 5, 6 Shows the temporal trace of the pulse sequences, which is recorded by the photodetector and an oscilloscope (Rohde & Schwarz, RTM 3004). Combing the RF spectrum and the temporal profile of the laser pulses, we could verify that no Q-switching modulations arises in the pulse trains.

4 Conclusion

In conclusion, we have demonstrated a fiber laser pumped 1.04 GHz Yb:CYA femtosecond Kerr-lens mode-locked laser, which is, to the best of our knowledge, the first gigahertz ever reported for all-solid-state Yb:CYA laser. The pulse duration is measured to be 99 fs with the maximum output power of 1.46 W. The optical spectrum of the femtosecond laser is 20 nm FWHM centered at 1048 nm, corresponding to 54 fs Fourier transfer limited pulse duration. Therefore, with optimized dispersion management, even shorter pulse durations could be obtained. The developed oscillator with nJ-level pulse energy is appropriate for the succeeding spectral broadening by use of the photonic crystal fiber and for the CEO detection in the f-2f interferometer. Such results would provide suitable sources for broadband dual-comb spectroscopy with sufficient resolution, optical bandwidth as well as the sampling time.

Data availability statement

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

Author contributions

ZZ, JM, and, GZ contributed to the laser design and experimental schemes, and performed the experiments. They are also responsible for the data processing. YZ contributed to the data processing. ZZ, HH, and ZW contributed to write and edit the manuscript. All authors contributed to the article and approved the submitted version.

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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.

Publisher's note

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