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Citation: Chin. Phys. B, 2025, 34 (**8**): 084204. DOI: 10.1088/1674-1056/adcf8b
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Chin. Phys. B, 2015, 24 (**2**): 024213. DOI: 10.1088/1674-1056/24/2/024213

Generation of Watt-level Kerr-lens mode-locked Yb:CYA laser at 1-GHz repetition rate

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(Received 22 March 2025; revised manuscript received 21 April 2025; accepted manuscript online 23 April 2025)

We report on a Kerr-lens mode-locked (KLM) femtosecond Yb:$CaYAlO_4$ (Yb:CYA) laser operating at a repetition rate of 1.04 GHz, pumped by a single-mode fiber laser. The laser delivers an average output power of 1.37 W with a pulse duration of 109 fs. Potential improvements, including scaling the pump power, increasing the repetition rate, and further reducing the pulse duration, are discussed. This study contributes to the advancement of Watt-level GHz femtosecond laser generation and its applications.

Keywords: all-solid-state ultrafast laser, high repetition rate, Kerr-lens mode-locking, Yb:CYA

PACS: 42.65.Re, 42.60.Da, 42.55.Rz, 42.55.Xi

DOI: 10.1088/1674-1056/adcf8b **CSTR:** 32038.14.CPB.adcf8b

1. Introduction

Gigahertz (GHz) repetition-rate femtosecond mode-locked lasers have wide potential applications in ultra-high-speed optical communications,[1] nonlinear biological-imaging, and spectroscopy,[2] especially in the generation of optical frequency combs.[3] High-repetition rate optical frequency combs can be applied in a variety of fields, such as broadband saturation absorption spectroscopy,[4] ultra-high-speed dual-optical comb spectral sampling,[5] optical arbitrary waveform generation,[6] aerospace,[7] and astronomical spectrometer calibration.[8] These lasers offer unique advantages in high-precision and high-speed optical systems, driving significant research interest in high-repetition-rate, high-power femtosecond sources.

Since the discovery of KLM in Ti:sapphire lasers in 1991,[9] numerous studies have been conducted towards shorter pulses[10,11] and higher power,[12,13] particularly achieving high repetition rates up to 10 GHz in such lasers.[14,15] Due to the high cost of pump source, large volume, low output power, and serious thermal effect, the application of Ti:sapphire lasers is limited. In contrast, ytterbium-doped (Yb-doped) materials are considered to be the most promising candidates for the generation of high-repetition rate, high-power femtosecond lasers due to their large emission cross-section, high quantum efficiency, long fluorescence lifetime, and excellent thermal properties. The commonly used mode locking schemes for solid-state Yb-doped lasers include passive mode-locking based on semiconductor saturable absorber mirror (SESAM) and Kerr-lens mode-locking (KLM). Solid-state Yb-doped lasers based on SESAM passive mode-locking offer several advantages, including high output laser stability, flexible parameter design, ease of adjustment, and self-starting mode-locking. A series of remarkable results have been achieved.[16–19] Compared with SESAM mode-locking, KLM has a shorter pulse build-up time and greater potential for ultra-short pulse generation. Typically, the Yb-doped crystals that produce femtosecond lasers also exhibit good third-order nonlinear coefficients, and no additional devices are required to achieve KLM, which leads to a significant reduction in the cost of the laser system. Thus, it has sparked a wave of research on KLM lasers. Yb-doped crystals based on $KGd(WO_4)_2$ (KGW),[20] $KY(WO4)_2$ (KYW),[21] $CaGdAlO_4$ (CALGO),[22,23] $CaYAlO_4$ (CYA),[24,25] and $LuYSiO_5$ (LYSO)[26] have achieved remarkable results. In recent years, numerous advancements have been made in the field of KLM, such as high-power thin-disk oscillators operating at 0.5 GHz,[27] distributed Yb:YAG thin-disk oscillator[28] and direct KLM Tm:$LuYO_3$ ceramic laser,[29] enriching the research and achievements in the KLM field. However, achieving Watt-level, GHz-repetition-rate KLM lasers presents several challenges: (i) low intracavity pulse energy at high repetition rates weakens the Kerr effect, requiring tight beam focusing; (ii) excellent pump beam quality is essential for precise focusing, limiting pump source options; (iii) precise dispersion management is complicated by the constrained

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cavity geometry with limited optical elements; and (iv) KLM initiation requires operation near the edges of the cavity's stability region, increasing mode-locking difficulty.

In this work, we address these challenges by selecting a high-brightness single-mode fiber laser as the pump source, utilizing an *a*-cut Yb:CYA crystal as the gain medium, and designing a tightly focused bow-tie ring cavity with optimized dispersion management. We achieve a 109-fs pulse at 1.04 GHz with an average power of 1.37 W. Compared to our previous work, this study uniquely combines high power (1.37 W), a GHz repetition rate (1.04 GHz), and short pulse duration (109 fs) in a KLM Yb:CYA laser. We conclude with perspectives on further optimizing the repetition rate, power, and pulse duration. This work will support and facilitate the research and application of KLM lasers with high repetition rates.

2. Experiment setup and design of laser cavity

The laser cavity, as shown in Fig. 1, consists of four main elements: concave mirrors M1 and M2, a plane Gires–Tournois interferometer (GTI) mirror M3, a Yb:$CaYAlO_4$ crystal (Yb:CYA), and an output coupler (OC). The laser is pumped by a 976-nm single-mode fiber laser. The cavity design is described in detail below.

Soft-aperture KLM lasers often require a tightly focused structure, where the focused spot of the pump light must be slightly smaller than the laser beam waist to achieve mode-locking conditions. We compare three pump sources: single-mode laser diodes (LDs), multimode LDs, and single-mode fiber lasers. Single-mode LDs offer high beam quality ($M^2 \approx 1.05$) but are limited to ~ 1 W, insufficient for high-power KLM. Multimode LDs provide higher power but poorer beam quality ($M^2 > 10$), yielding a focused spot size > 100 μm, too large for KLM. Single-mode fiber lasers combine high power (> 8 W), excellent beam quality ($M^2 < 1.1$), and a focused spot diameter that can easily reach less than 30 μm, making them ideal for GHz-repetition-rate KLM. In this experiment, a high-brightness, Yb-doped single-mode fiber laser is used to provide an average power of up to 8.07 W at the center wavelength of 976 nm.

To achieve a high repetition rate, short pulse duration, and high-power laser output, the importance of selecting a suitable gain crystal cannot be overstated. Ytterbium-doped yttrium calcium aluminate (Yb:$CaYAlO_4$, abbreviated Yb:CYA) crystals belong to the tetragonal system, which can be easily grown by the Czochralski process. The crystal exhibits a wide and flat emission bandwidth of up to 77 nm, supporting the output of femtosecond pulses. At room temperature, a Yb:CYA crystal with a doped concentration of 1% has a specific heat capacity of 0.593 $J{\cdot}g^{-1}{\cdot}K^{-1}$, and its thermal conductivity along the *a*-axis and *c*-axis is 3.6 $W{\cdot}m^{-1}{\cdot}K^{-1}$ and 3.2 $W{\cdot}m^{-1}{\cdot}K^{-1}$, respectively. This means that the Yb:CYA crystal has a high damage threshold and can be pumped with higher power lasers.[30] The thermal coefficient of the optical path (TCOP) of *c*-cut Yb:CYA crystal is 5.9×10^{-6} K^{-1}, while that of *a*-cut crystal is 1.2×10^{-6} K^{-1}, a difference of nearly 4 times. Compared with the *c*-cut crystal, the *a*-cut Yb:CYA crystal is more suitable for high power lasers due to its reduced thermal effects.[31] Because of the excellent optical, thermal, and mechanical properties of Yb:CYA crystals, the corresponding research results are emerging and important parameters have been broken through. Over the past few years, lasers with a repetition rate of 1.8 GHz,[32] a pulse duration of 17 fs,[33] and a power output exceeding 20 W[34] have appeared, demonstrating that the Yb:CYA crystals are ideal for producing lasers with high repetition rate, high power, and short pulse duration. In this study, a 3-mm-long, *a*-cut 8%-doped Yb:CYA crystal is used as the gain medium. The crystal, with a 3 mm×3 mm cross-section, is antireflection-coated for 900 nm–1200 nm on both faces. To reduce the thermal lens effect caused by uneven temperature distribution, the crystal is mounted on a copper heat sink and cooled to 18 °C with circulating water to eliminate heat accumulation in the crystal.

For Kerr-lens mode-locked lasers with gigahertz (GHz) repetition rate, the main difficulty in their implementation is the week Kerr effect. Therefore, the design of the GHz repetition-rate resonator is critical. Laser cavities generally adopt linear or ring configurations. To achieve a GHz repetition rate in a linear cavity, the cavity length generally needs to be less than 150 mm, while the length of a ring cavity can be up to 300 mm. By contrast, a ring cavity of the same size is more conducive to increasing the repetition rate. Therefore, we use a ring cavity with a butterfly-shaped structure in our oscillator design. As shown in Fig. 1, M1 and M2 are both concave mirrors with a curvature radius of 50 mm, and M2 and M3 are both GTI mirrors. M1 is used as a pump mirror, with high transmittance at a pump wavelength of 976 nm and high reflectivity at an oscillation wavelength centered at 1046.8 nm. M3 is a 1-inch (1 inch = 2.54 cm) plane mirror. To ensure high power output and sufficiently high intracavity laser intensity to enhance the Kerr effect, an output coupling mirror (OC) with a transmittance of 1.6% is used. The total cavity length of the four-mirror ring cavity is 288 mm, and the corresponding repetition frequency is 1.04 GHz. Since the 976-nm fiber laser is divergent when emitted, the pump light is first collimated by a convex lens L1 ($f = 300$ mm) and then focused by a second convex lens L2 ($f = 50$ mm). The focused pump spot diameter at the center of the gain medium is approximately 43 μm ($1/e^2$). According to the ABCD transmission matrix, the mode size of the circulating laser in the

crystal is about 56 μm, which is slightly larger than the pump spot size and suitable for soft-aperture KLM.

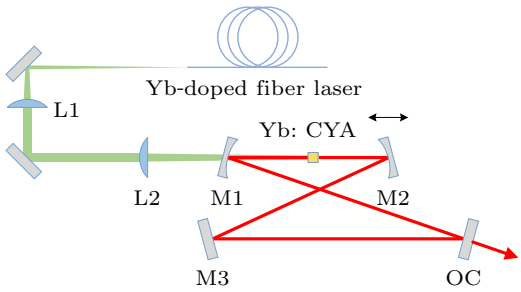


Fig. 1. Experiment setup of the 1-GHz repetition-rate laser.

The high repetition rate limits the number of optics available in the cavity, making dispersion compensation more challenging. Therefore, both the concave mirror M2 and the plane mirror M3 are chosen to be GTI mirrors, which can provide a one-way group delay dispersion (GDD) of -1350 fs^2, similar to that in the reference.[35] Among them, M2 has $>99.9\%$ reflectivity in the band near 1040 nm and provides -550-fs^2 GDD, while M3 has $>99.9\%$ reflectivity in the band from 1000 nm to 1160 nm and provides a GDD of approximately -800 fs^2. Yb:CYA crystals exhibit a material GVD of ~ 85 fs^2/mm at 1 μm,[31] resulting in a total GDD of $+255$ fs^2 for a 3-mm-long crystal. The net total intracavity GDD per round trip amounts to -1095 fs^2.

3. Results and discussion

Initially, the continuous wave (CW) output power of the laser is adjusted to its maximum by optimizing the cavity mirror. During CW operation, the laser outputs in both clockwise and counterclockwise directions. The ring cavity has only one stability region, and the stability region is very long, allowing the concave mirror to achieve stable CW output over a long distance. However, locating the KLM position remains challenging. According to the literature, it is easier to achieve modelocking near the inner stability edge.[36] To find the mode-locking position, we can translate the concave mirror M2 toward the crystal and use a high-speed avalanche photodiode (APD) detector and oscilloscope to measure the pulse sequence of the output laser in real time. When the power becomes unstable and the output spot changes to a long strip-like high-order mode output, fine-tuning the position of the end mirror and the crystal can achieve passive mode-locking. Once modelocked, the laser operates in a random direction. To avoid the influence of the pump laser, it may be necessary to restart the mode-locking process until the laser output in the direction shown in Fig. 1 is obtained.

When mode-locking is initiated, the output power increases to 1.37 W at the main output beam, while the power of the other output beam drops to an extremely low level. The spectra of the mode-locked pulses were measured by a spectrometer (AQ6370C, YOKOGAWA), and figure 2(a) shows a spectrum centered at 1046.8 nm with a full width at half maximum (FWHM) bandwidth of 11.2 nm, corresponding to a Fourier transform limiting pulse duration of 103 fs. Assuming the pulse shape is hyperbolic secant square (sech^2), the corresponding pulse duration is measured to be 109 fs, as shown in Fig. 2(b). The time-bandwidth product of the pulse is 0.334, which is close to the theoretical limit of 0.315 for sech^2-shaped pulses. The mode-locked spectra exhibit a strong spectrum peak near 1100 nm, which is a dispersion wave[37] caused by the limitation of the dispersion compensation bandwidth of the intracavity GTI mirror.

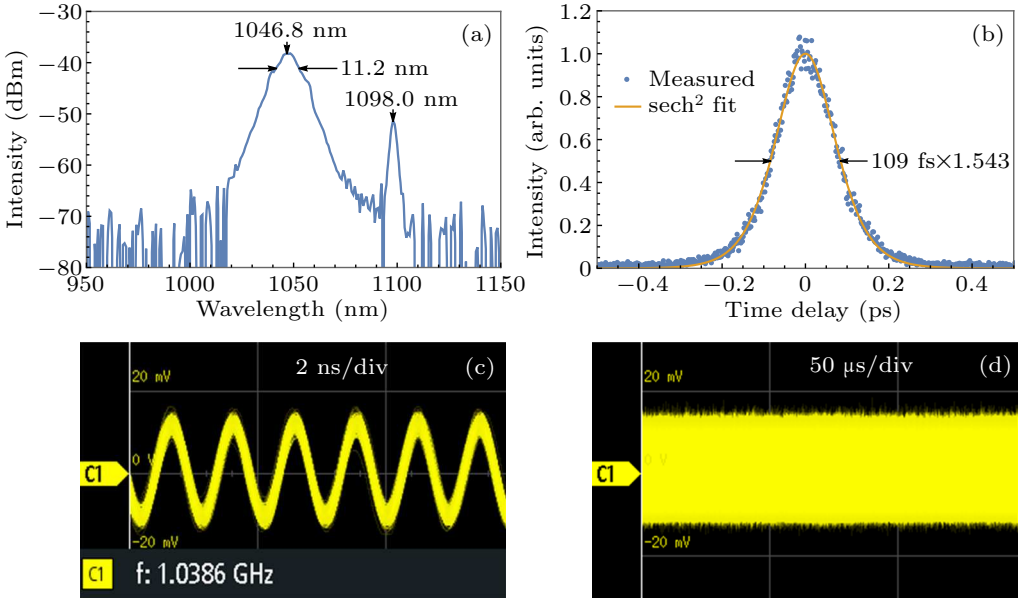


Fig. 2. Output performances of the 1-GHz KLM Yb:CYA laser. (a) Optical spectrum, (b) the intensity auto-correlation trace. Mode-locked pulse trains in nanosecond (c) and microsecond (d) time scales.

We used an oscilloscope with a bandwidth of 1 GHz (RTM3004, Rohde & Schwarz) to measure the pulse train. As shown in Fig. 2(c), the Yb:CYA oscillator operates at a 1.04-GHz repetition rate. From Fig. 2(d), we observed that the laser is in a very stable continuous mode-locked state, and there is no *Q*-switched envelope present.

4. Conclusion and perspectives

We have demonstrated a Watt-level, GHz-repetition-rate femtosecond laser. Using a bow-tie cavity pumped by a single-mode fiber laser with Yb:CYA as the gain medium, we achieved a laser output with a repetition frequency of 1.04 GHz, an average power of 1.37 W, and a pulse duration of 109 fs. For power scaling, in addition to the expectation of a breakthrough in performance from a high-brightness pump source, the use of high-power multimode LDs and dual-confocal cavities[38] to separate the gain medium from the Kerr medium is also a good option. Shorter pulse widths can be achieved by optimizing the cavity GDD[39] or by using a gain-matched output coupler[40] to achieve a smoother spectrum, supporting pulses approaching few-cycle durations. Shortening the cavity length can increase the repetition rate to 15 GHz,[41] though this may heighten challenges in dispersion management and cavity stability. To further increase the repetition rate, novel cavity designs can be utilized.[42]

Data availability statement

The data that support the findings of this study are openly available in Science Data Bank at the following link https://doi.org/10.57760/sciencedb.j00113.00237.

Acknowledgement

Project supported by the National Key Research and Development Program of China (Grant No. 2022YFB4600158).

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