Research Article | Vol. 6, No. 2 / February 2018 / Photonics Research 127

PHOTONICS Research

Diode-pumped power scalable Kerr-lens mode-locked Yb:CYA laser

WENLONG TIAN,[1] YINGNAN PENG,[1] ZIYUE ZHANG,[2] ZIJIAO YU,[2] JIANGFENG ZHU,[1,*] XIAODONG XU,[3] AND ZHIYI WEI[2]

[1]School of Physics and Optoelectronic Engineering, Xidian University, Xi'an 710071, China
[2]Beijing National Laboratory for Condensed Matter Physics and Institute of Physics, Chinese Academy of Sciences, Beijing 100190, China
[3]Jiangsu Key Laboratory of Advanced Laser Materials and Devices, School of Physics and Electronic Engineering, Jiangsu Normal University, Xuzhou 221116, China
*Corresponding author: jfzhu@xidian.edu.cn

Received 20 October 2017; revised 5 December 2017; accepted 11 December 2017; posted 11 December 2017 (Doc. ID 309535); published 25 January 2018

Stable 68 fs pulses with the average power of 1.5 W is directly generated from a multimode diode-pumped Kerr-lens mode-locked Yb:CYA laser by separating the gain medium and Kerr medium. The repetition rate is about 50 MHz, resulting in a single pulse energy of 30 nJ and a peak power of 0.44 MW. To the best of our knowledge, this is the highest single pulse energy ever produced from a mode-locked Yb:CYA oscillator. Our experimental results show that Yb:CYA crystal is an excellent candidate for multiwatt, sub-100 fs pulse generation in diode-pumped all-solid-state lasers. It is believed that the output power can be scalable to multi-W while the pulse duration is maintained with this simple method.

OCIS codes: (140.4050) Mode-locked lasers; (140.3615) Lasers, ytterbium; (140.3580) Lasers, solid-state.

https://doi.org/10.1364/PRJ.6.000127

1. INTRODUCTION

High-power femtosecond lasers have versatile applications in industrial, medical, and scientific researches and have long attracted a wide range of investigations. In the near-infrared band, Yb-doped active mediums are well known as optimal alternatives in this aspect, and various kinds of Yb-doped materials have been reported [1–8]. Among them, Yb-doped $CaGdAlO_4$ (shorted as Yb:CGA or Yb:CALGO) is one of the most attractive candidates due to its excellent spectroscopic and thermal properties [9]. Because of its disordered structure resulting in broad and flat emission spectra, sub-50-fs pulses are able to be generated from laser diode (LD) pumped mode-locked Yb:CGA oscillators by means of either semiconductor saturable absorber mirrors (SESAMs) [10] or Kerr-lens mode-locking (KLM) [11]. In addition, the high thermal conductivity of Yb:CGA crystal allows for high-power pumping and high-power outputting. In 2012, Greborio *et al.* reported a high-power SESAM passively mode-locked Yb:CGA laser delivering as high as 12.5 W average power and 94 fs pulse duration [12]. Recently, Sévillano *et al.* demonstrated a pure KLM Yb:CGA oscillator pumped by a diffraction-limited fiber laser [8]. Due to the high brightness as well as excellent polarization property of the fiber laser, as short as 40 fs pulses with 1.1 W average power were obtained. Most recently, Manjooran and Major reported on the direct generation of sub-50 fs pulses with >1.5 MW peak power from a diode-pumped Yb:CGA laser, which is the highest-peak-power diode-pumped bulk laser oscillator in the sub-50-fs category [13].

As another Yb-doped calcium aluminate crystal, Yb:$CaYAlO_4$ (shorted as Yb:CYA or Yb:CALYO) has similar spectroscopic property as Yb:CGA crystal but is easier to grow and fabricate. Due to the charge difference between Ca^{2+} and Y^{3+} ions and their random distributions, the emission spectrum of Yb:CYA has largely inhomogeneous broadening, resulting in as broad as 77 nm full width at half-maximum (FWHM) bandwidth at σ polarization [14]. In addition, Yb:CYA crystal has relatively higher specific heat capacity, which means a larger optical damage threshold, while its thermal conductivity is moderate. Recently, Loiko *et al.* investigated the Sellmeier equations, group velocity dispersion, and thermo-optic dispersion formulas of CYA laser host crystal, showing that the thermo-optic properties of CYA are slightly better than those of CGA, which makes Yb:CYA promising for power-scalable lasers [15]. Benefiting from the above-noted advantages, Yb:CYA crystal attracts increasing interest in ultrashort pulse generation. The first femtosecond Yb:CYA oscillator was reported in 2011, producing laser pulses of 156 fs with an average output power of 740 mW [16]. Dissipative soliton operation of a Yb:CYA laser was also reported with 7.4 ps uncompressed pulses and 340 fs compressed ones [17]. Due to the broad and flat emission spectrum, Pirzio *et al.* demonstrated a sub-50 fs widely tunable Yb:CYA laser with shortest pulse duration of 43 fs and a wavelength tunability of 40 nm [18]. Recently, as short as 33 fs pulses [19] and a record pulse duration of 30 fs [20] were achieved from a KLM Yb:CYA oscillator and a passively mode-locked Yb:CYA oscillator with graphene, respectively. However, only several tens of mW average power was generated from these ultrashort pulse oscillators, which is mainly attributed to the critical cavity setup restrained by the low-brightness of the fiber-coupled laser diode. On the other hand, employing a single-mode fiber laser, which has high brightness as well as excellent linear-polarization property, is an alternative way to cope with this issue. Yu *et al.* implemented a fiber-laser-pumped KLM Yb:CYA laser providing 250 mW output power and 57 fs pulse duration, which was used to develop an optical frequency comb [21]. However, the single-mode fiber laser is costlier and has lower power than the commonly used multimode LDs. Hence, it is significant to develop a high-power sub-100-fs Yb:CYA laser pumped by a multimode LD. In general, the Kerr effect strongly depends on the mode radius inside the Kerr medium. One usually employs a tight focusing cavity to enhance the Kerr-lens effect for generating ultrashort pulses, which is incompatible with the large pump spot of a multimode LD, resulting in not only bad mode matching as well as low efficiency but also multimode operation. An effective way we propose here is to separate the gain medium and Kerr medium in a double confocal cavity, which has been confirmed in a Kerr-lens mode-locked Yb:YAG thin disk laser [21]. By doing so, we can release the restrain imposed on the laser crystal, which usually acts in the double role of gain medium and Kerr medium. As a result, a high-power ultrashort femtosecond KLM operation is feasible.

In this paper, we demonstrated a multimode LD-pumped high-power KLM Yb:CYA laser by introducing an extra Kerr-medium to separate the gain material and Kerr material. By arranging a small spot on the Kerr material to obtain enough Kerr-lens effect while excellent mode-matching between the laser and pump, as high as 1.5 W average power and down to 68 fs pulses at the central wavelength of 1040 nm are directly obtained. With the pulse repetition rate of 50 MHz, the single pulse energy is 30 nJ, which is the highest single pulse energy ever achieved from the Yb:CYA oscillators, corresponding to the peak power of 0.44 MW.

2. EXPERIMENTAL SETUP

Figure 1 shows the sketch of the experimental setup. In order to realize high-power mode-locking, an extra Kerr medium of 2 mm thick quartz as well as an aperture was introduced in the cavity. An immediate result is that the laser gain medium, a 2 mm thick c-cut 8 at. % doped Yb:CYA crystal, is no longer necessary to act as a Kerr medium; as a result, a higher pump power with larger beam spot size is allowed to be incident on the laser crystal. Thus, we used a fiber-coupled LD emitting at 976 nm with the maximum output power of 25 W, whose core diameter is 105 μm, as the pump source. An imaging system with a magnification of 1∶1 was used to couple the pump laser from the fiber into the Yb:CYA crystal, resulting in a focused pump spot diameter of about 105 μm. To effectively eliminate the heat accumulation and maintain a stable temperature, the uncoated gain crystal placed at Brewster′s angle was wrapped with indium foil and mounted on a heat sink kept at 14°C by cycling water. Without laser effect, the absorption efficiency for the pump power of the Yb:CYA crystal was measured to be 43%. Concave mirrors C1 and C2 both have the same radius of curvature (ROC) of 300 mm. The beam waist inside the quartz should be small enough to enhance the Kerr-lens effect. Here, we utilized two concave mirrors of C3 and C4 with both ROC of 100 mm, and the quartz plate was positioned at the center between C3 and C4. Two Gires–Tournois interferometer mirrors (GTIs) with the total group velocity dispersion of $-1850\ \mathrm{fs}^2$ per bounce in the 1035–1055 nm range were used for dispersion compensation. M1 was a dichroic mirror with high transmittance for pump and high reflectivity for 1 μm laser. M2 and M3 were flat mirrors with high reflective coating from 1020 to 1100 nm. The output coupler (OC) with 2.5% transmittance was mounted on a precise translation stage. The total cavity length was about 3 m, corresponding to the repetition rate of 50 MHz.

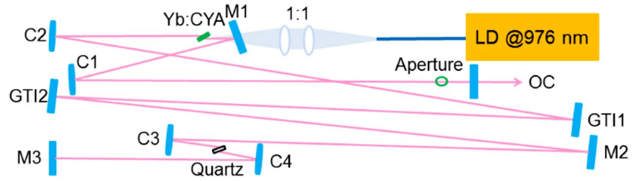

Fig. 1. Experimental setup of the high-power Kerr-lens mode-locked Yb:CYA laser. C1 and C2, concave mirrors with ROC of 300 mm; GTI1 and GTI2, Gires–Tournois interferometer mirrors with total dispersion of $-1850\ \mathrm{fs}^2$ per bounce; C3 and C4, concave mirrors with ROC of 100 mm; M1, dichroic mirror; M2 and M3, flat mirrors with high reflectivity; OC, output coupler with transmittance of 2.5%.

At first, we aligned the laser cavity to optimize the output power under continuous wave (CW) operation without the aperture. The maximum output power was 2 W with 25 W incident pump power as shown in Fig. 2, corresponding to the slope efficiency of 13.3%. Based on the ABCD matrix, the laser beam waists at the center of Yb:CYA crystal and the quartz plate were about 121 μm and 48 μm, respectively.

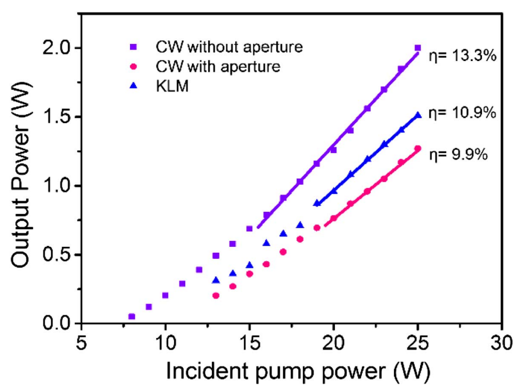

Fig. 2. Output performances of the continuous wave (CW) and Kerr-lens mode-locked operations of Yb:CYA laser, respectively.

Then, the aperture was inserted in the cavity nearby the OC, acting as a hard aperture for KLM. By varying the aperture diameter from 1 to 3 mm, it was found that the aperture with a diameter of 2.6 mm fits the best performance of Kerr-lens mode-locking. With such an aperture, the maximum CW output power dropped to 1.3 W at first. Then, after finely tuning the position of C4 to the edge of the stable region, KLM was easily realized by fast moving the translation stage of the OC, with the maximum average output power increased to 1.5 W. We measured the power scalable of the KLM mode-locking operation, as shown in Fig. 2. The KLM could be sustained until the pump power decreased to 13 W.

The central wavelength was at 1046 nm under CW operation while at 1040 nm under KLM operation. By optimizing the position of the quartz in the cavity, the broadest optical spectrum of the KLM pulses had a FWHM bandwidth of 14.5 nm, as shown in Fig. 3(a). Via Fourier transform with zero chirp, the transform-limited pulse duration is 61.8 fs if a sech^2 pulse shape is assumed. The corresponding intensity autocorrelation trace was measured by a commercial intensity auto-correlator (APE PulseCheck USB), as shown in Fig. 3(b). The FWHM bandwidth of the autocorrelation trace was about 104 fs, corresponding to 68 fs pulse duration, which was close to the Fourier limited pulse duration. The beam profile of the stable KLM pulses was near fundamental Gaussian shape with a bit ellipse, detected by a commercial optical beam analyzer, as inserted in Fig. 3(a). The single pulse operation was certified by the only one peak of the autocorrelation trace observed in a broad time delay span of 50 ps. In addition, the pulse train was recorded by using a 500 MHz bandwidth oscilloscope, as depicted in Fig. 4. There was no visible Q-switching modulation of the mode-locked pulse train.

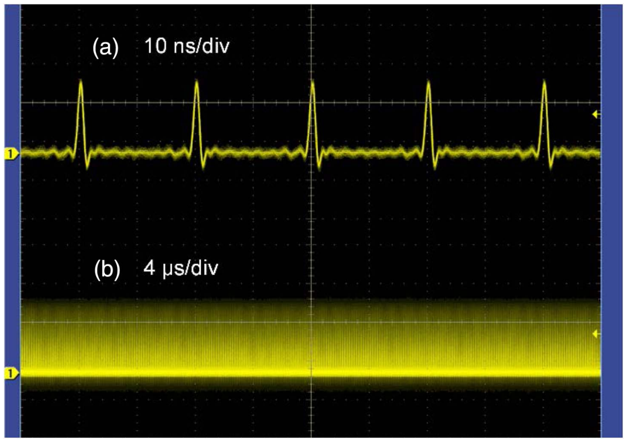

Fig. 4. Oscilloscope traces of the high-power Kerr-lens mode-locked pulse train in the time scales of (a) 10 ns/div, and (b) 4 μs/div, respectively.

To claim the status of the mode-locking operation, the radio frequency (RF) spectrum was also measured via a photodetector (PD) with a 3 dB bandwidth of 1 GHz and a commercial RF spectrum analyzer (R&S FSVA40). The signal was recorded for both a frequency window of 1 MHz with 1 kHz resolution

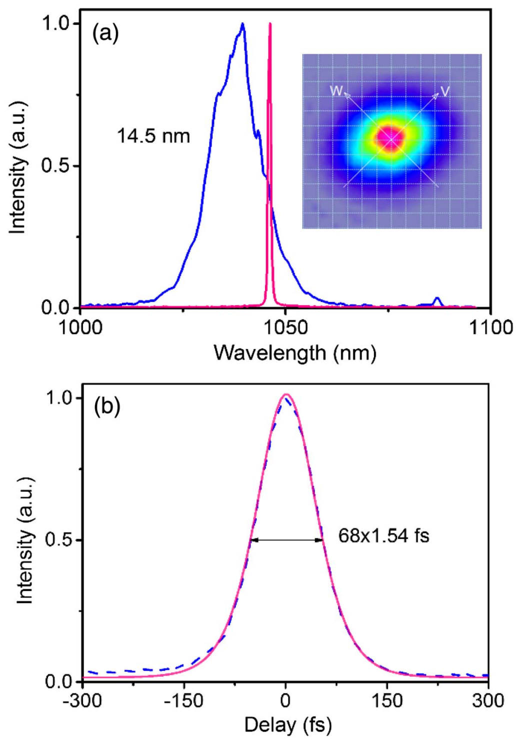

Fig. 3. Pulse characterization results of the KLM Yb:CYA laser. (a) CW (red) and mode-locked (blue) spectra, inset is the beam profile at the maximum average power of 1.5 W. (b) Measured intensity autocorrelation trace shown as black dashed while the fitted sech^2 trace shown by red solid curve.

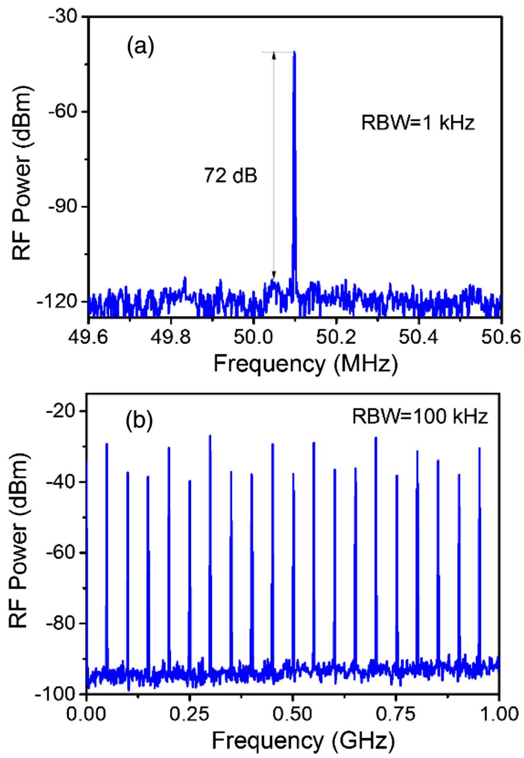

Fig. 5. RF spectra of the Kerr-lens mode-locked Yb:CYA laser. (a) RF spectrum at the fundamental beat note with the resolution bandwidth of 1 kHz. (b) RF spectrum at 1 GHz wide-span range with the resolution bandwidth of 100 kHz.

bandwidth (RBW) and a window of 1 GHz with 100 kHz RBW, as described in Fig. 5. The distinct signal-to-noise ratio of the fundamental beat note at 50.1 MHz was as high as 72 dBc. Stable mode-locking operation was illustrated by the clean RF spectrum, where no side peaks of the harmonics of the fundamental frequency were observed, as shown in Fig. 5(b). The fluctuation of the harmonics peaks in Fig. 5(b) might be originated from the limited sampling rate of the RF spectrum analyzer. Once started by slight perturbation, the mode-locking operation could last stably for several hours in open air.

3. CONCLUSION

We summarized the state-of-the-art results from Yb-based bulk lasers in generating sub-100 fs pulses with watt-level output power, as shown in Fig. 6. Previously, Yb-based bulk lasers delivering watt-level sub-100 fs pulses have been reported only with a few kinds of gain media, such as Yb:CaF_2 [5,22], Yb:CGA [8,12,13], Yb:KYW [23], Yb:KGW [4,6,24], and Yb:Lu_2O_3 [25] crystals as well as Yb:LuAG ceramic [1]. Among them, Yb:CGA crystal provides not only the highest peak power as well as average output power but also the shortest pulse duration. Belonging to the same calcium aluminate family, Yb:CYA crystal has also been given high expectations. However, no similar work has been previously reported.

In this paper, we have demonstrated a diode-pumped watt-level KLM Yb:CYA laser for the first time, to the best of our knowledge. As short as 68 fs pulses centered at 1040 nm with the average output power up to 1.5 W have been generated directly from the oscillator by separating the gain crystal and the Kerr medium. With a repetition rate of 50 MHz, the corresponding single pulse energy and the peak power are as high as 30 nJ and 0.44 MW, respectively, both are the highest ones from the Yb:CYA oscillators. Considering the broad and flat emission spectra of Yb:CYA, shorter pulses of sub-50 fs with watt-level average power are expected with several improvements. For instance, different kinds of Kerr media with higher nonlinear refractive indices such as YAG or sapphire could be used to strengthen the self-phase modulation. Combining with meticulous dispersion management, high-power single-pulse operation should be compatible with short pulse duration. On the other hand, the maximum output power of 1.5 W at present is limited not only by the mode mismatching in the Yb:CYA crystal between the pump and the laser—the beam diameter of the latter is about twice that of the former—but also by the limited pump power. No obvious thermal distortion or multipulse operation was observed, indicating higher pump power is endurable to produce higher average power. In addition, Loiko *et al.* recently demonstrated the microchip Yb:CYA laser delivering 5.06 W power in CW operation with a recorded high slope efficiency of 91% [27], which also indicates the power scaling potential of Yb:CYA crystal. Thus, multiwatt sub-100 fs pulse generation is feasible from the Yb:CYA oscillator and will find wide application in many fields.

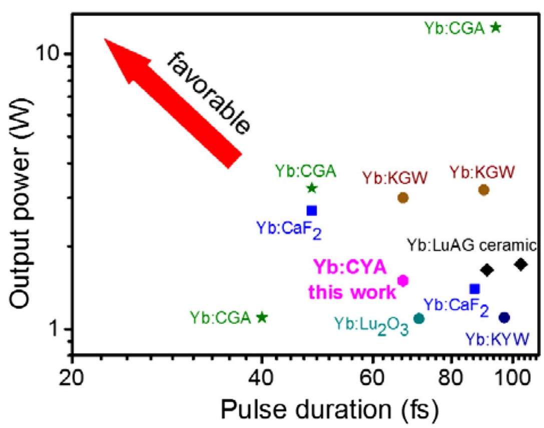

Fig. 6. Summary of the sub-100 fs mode-locked lasers based on bulk Yb-doped crystals with watt-level average output power [1,4–6,8,12,13,22–26].

Funding. National Key Basic Research Program of China (2013CB922402); National Natural Science Foundation of China (NSFC) (61705174, 11774277); Fundamental Research Funds for the Central Universities (JBX170511); Open Fund of IPOC (BUPT) (IPOC2016B009); 111 Project (B17035).

REFERENCES

1. S. Kitajima, H. Nakao, A. Shirakawa, H. Yagi, and T. Yanagitani, "Kerr-lens mode-locked Yb^{3+}-doped $Lu_3Al_5O_{12}$ ceramic laser," Opt. Lett. **41**, 4570–4573 (2016).
2. I. Tomohiro, A. A. Eilanlou, N. Yasuo, F. Yoshihiko, I. Tomohiro, S. Tetsumi, K. Fumihiko, K.-G. Makoto, and M. Katsumi, "Kerr lens mode-locked Yb:Lu_2O_3 bulk ceramic oscillator pumped by a multimode laser diode," Jpn. J. Appl. Phys. **54**, 072703 (2015).
3. Z. Gao, J. Zhu, W. Tian, J. Wang, Z. Zhang, Z. Wei, H. Yu, H. Zhang, and J. Wang, "Generation of 73 fs pulses from a diode pumped Kerr-lens mode-locked Yb:$YCa_4O(BO_3)_3$ laser," Opt. Lett. **39**, 5870–5872 (2014).
4. H. Zhao and A. Major, "Powerful 67 fs Kerr-lens mode-locked prismless Yb:KGW oscillator," Opt. Express **21**, 31846–31851 (2013).
5. F. Pirzio, S. D. Di Dio Cafiso, M. Kemnitzer, F. Kienle, A. Guandalini, J. Aus der Au, and A. Agnesi, "65-fs Yb:CaF_2 laser mode-locked by semiconductor saturable absorber mirror," J. Opt. Soc. Am. B **32**, 2321–2325 (2015).
6. V. E. Kisel, A. S. Rudenkov, A. A. Pavlyuk, A. A. Kovalyov, V. V. Preobrazhenskii, M. A. Putyato, N. N. Rubtsova, B. R. Semyagin, and N. V. Kuleshov, "High-power, efficient, semiconductor saturable absorber mode-locked Yb:KGW bulk laser," Opt. Lett. **40**, 2707–2710 (2015).
7. W. Tian, Z. Wang, J. Zhu, L. Zheng, J. Xu, and Z. Wei, "Highly efficient and high-power diode-pumped femtosecond Yb:LYSO laser," Laser Phys. Lett. **14**, 045802 (2017).
8. P. Sévillano, P. Georges, F. Druon, D. Descamps, and E. Cormier, "32-fs Kerr-lens mode-locked Yb:$CaGdAlO_4$ oscillator optically pumped by a bright fiber laser," Opt. Lett. **39**, 6001–6004 (2014).
9. F. Druon, J. Boudeile, Y. Zaouter, M. Hanna, F. Balembois, P. Georges, J. Petit, P. Golner, and B. Viana, "New Yb-doped crystals for high-power and ultrashort lasers," Proc. SPIE **6400**, 64000D (2006).
10. A. Agnesi, A. Greborio, F. Pirzio, G. Reali, J. Aus der Au, and A. Guandalini, "40-fs Yb^{3+}:$CaGdAlO_4$ laser pumped by a single-mode 350-mW laser diode," Opt. Express **20**, 10077–10082 (2012).
11. Z. Gao, J. Zhu, J. Wang, Z. Wang, Z. Wei, X. Xu, L. Zheng, L. Su, and J. Xu, "Diode-pumped Kerr-lens mode-locked Yb:$CaGdAlO_4$ laser with tunable wavelength," Laser Phys. Lett. **13**, 015302 (2016).
12. A. Greborio, A. Guandalini, and J. Aus der Au, "Sub-100 fs pulses with 12.5-W from Yb:CALGO based oscillators," Proc. SPIE **8235**, 823511 (2012).

13. S. Manjooran and A. Major, "Generation of sub-50 fs pulses with >1.5 MW of peak power from a diode-pumped Yb:CALGO laser oscillator," in *Conference on Lasers and Electro-Optics (CLEO)* (2016), paper JTu5A.82.
14. D. Li, X. Xu, H. Zhu, X. Chen, W. D. Tan, J. Zhang, D. Tang, J. Ma, F. Wu, and C. Xia, "Characterization of laser crystal $Yb:CaYAlO_4$," J. Opt. Soc. Am. B **28**, 1650–1654 (2011).
15. P. Loiko, P. Becker, L. Bohatý, C. Liebald, M. Peltz, S. Vernay, D. Rytz, J. M. Serres, X. Mateos, Y. Wang, X. Xu, J. Xu, A. Major, A. Baranov, U. Griebner, and V. Petrov, "Sellmeier equations, group velocity dispersion, and thermo-optic dispersion formulas for $CaLnAlO_4$ (Ln:Y, Gd) laser host crystals," Opt. Lett. **42**, 2275–2278 (2017).
16. W. Tan, D. Tang, X. Xu, D. Li, J. Zhang, C. Xu, and J. Xu, "Femtosecond and continuous-wave laser performance of a diode-pumped $Yb^{3+}:CaYAlO_4$ laser," Opt. Lett. **36**, 259–261 (2011).
17. W. Tan, D. Tang, C. Xu, J. Zhang, X. Xu, D. Li, and J. Xu, "Evidence of dissipative solitons in $Yb^{3+}:CaYAlO_4$," Opt. Express **19**, 18495–18500 (2011).
18. F. Pirzio, S. D. Di Dio Cafiso, M. Kemnitzer, A. Guandalini, F. Kienle, S. Veronesi, M. Tonelli, J. Aus der Au, and A. Agnesi, "Sub-50-fs widely tunable $Yb:CaYAlO_4$ laser pumped by 400-mW single-mode fiber-coupled laser diode," Opt. Express **23**, 9790–9795 (2015).
19. Z. Gao, J. Zhu, J. Wang, Z. Wei, X. Xu, L. Zheng, L. Su, and J. Xu, "Generation of 33 fs pulses directly from a Kerr-lens mode-locked $Yb:CaYAlO_4$ laser," Photon. Res. **3**, 335–338 (2015).
20. J. Ma, H. Huang, K. Ning, X. Xu, G. Xie, L. Qian, K. P. Loh, and D. Tang, "Generation of 30 fs pulses from a diode-pumped graphene mode-locked $Yb:CaYAlO_4$ laser," Opt. Lett. **41**, 890–893 (2016).
21. Z. Yu, H. Han, Y. Xie, Y. Peng, X. Xu, and Z. Wei, "CEO stabilized frequency comb from a 1-μm Kerr-lens mode-locked bulk Yb:CYA laser," Opt. Express **24**, 3103–3111 (2016).
22. G. Machinet, P. Sevillano, F. Guichard, R. Dubrasquet, P. Camy, J. L. Doualan, R. Moncorgé, P. Georges, F. Druon, D. Descamps, and E. Cormier, "High-brightness fiber laser-pumped 68-fs 2.3-W Kerr-lens mode-locked $Yb:CaF_2$ oscillator," Opt. Lett. **38**, 4008–4010 (2013).
23. F. M. Bain, A. A. Lagatsky, C. T. A. Brown, and W. Sibbett, "High-power Kerr-lens mode-locked ytterbium lasers," Proc. SPIE **6871**, 68712L (2008).
24. R. Akbari and A. Major, "High-power diode-pumped Kerr-lens mode-locked bulk Yb:KGW laser," Appl. Opt. **56**, 8838–8844 (2017).
25. M. Tokurakawa, A. Shirakawa, K. Ueda, R. Peters, S. T. Fredrich-Thornton, K. Petermann, and G. Huber, "Ultrashort pulse generation from diode pumped mode-locked Yb^{3+}: sesquioxide single crystal lasers," Opt. Express **19**, 2904–2909 (2011).
26. S. Kitajima, H. Nakao, A. Shirakawa, H. Yagi, and T. Yanagitani, "Kerr-lens mode-locked Yb^{3+}-doped $Lu_3Al_5O_{12}$ ceramic laser," in *The European Conference on Lasers and Electro-Optics* (Optical Society of America, 2015), paper CA_2_5.
27. P. Loiko, J. M. Serres, X. Mateos, X. Xu, J. Xu, V. Jambunathan, P. Navratil, A. Lucianetti, T. Mocek, X. Zhang, U. Griebner, V. Petrov, M. Aguiló, F. Díaz, and A. Major, "Microchip $Yb:CaLnAlO_4$ lasers with up to 91% slope efficiency," Opt. Lett. **42**, 2431–2434 (2017).