Diode-pumped high-power sub-100 fs Kerr-lens mode-locked Yb:CaYAlO$_4$ laser with 1.85 MW peak power

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Abstract: We demonstrated a diode-pumped high-power Kerr-lens mode-locked Yb:CaYAlO$_4$ (Yb:CALYO) laser with a dual-confocal cavity, directly generating 59-fs pulses with 6.2 W average power, which is the highest average power from any sub-60 fs Yb-doped solid-state lasers. With the repetition rate of 50 MHz, the corresponding single pulse energy was 124 nJ and the peak power was 1.85 MW, which to the best of our knowledge is the highest peak power delivered directly from a sub-100 fs Yb-based bulk lasers ever.

1. Introduction

Over the past few decades, there has been great interest in the development of high-power femtosecond lasers for wide applications in industrial and scientific researches. At present, the most mature high-power femtosecond laser is the Kerr lens-mode-locked (KLM) Ti:sapphire laser, but the Ti:Sapphire laser is currently limited to the existing pump source power and the quantum efficiency of the crystal itself. As another excellent candidate for high power ultrashort pulses generation, Yb-doped materials have attracted increasing attentions due to their large emission bandwidth, high quantum efficiency, and excellent thermal properties. In addition, Yb-doped materials can be directly pumped by commercially high power laser diodes (LD), which gives them a significant advantage towards achieving high-power, compact and cost-effective femtosecond solid-state lasers.

So far, Yb-based bulk lasers delivering watt-level sub-100 fs pulses have been reported with a few kinds of gain media, such as Yb:CALGO [1–4], Yb:CaF$_2$ [5–7],Yb:CALYO [8], Yb:KGW [9–12], Yb:YSO [13], Yb:YVO$_4$ [14], and Yb:Lu$_2$O$_3$ [15] as well as Yb:LuAG ceramic [16]. Among them, Yb^{3+} doped CaGdAlO$_4$ (CALGO) crystal performed both the highest average power and shortest pulse duration, respectively, due to its excellent spectroscopic and thermal properties [17]. As the same member of Yb-doped calcium aluminate crystals, Yb:CaYAlO$_4$ (Yb:CALYO) which is easier to grow and fabricate also has similar properties including a broad fluorescence spectrum with the full width at half maximum (FWHM) of up to 77 nm at the σ polarization [18], and moderate thermal conductivities of Ka = 3.6 Wm^{-1}K^{-1} and Kc = 3.2 Wm^{-1}K^{-1} along it's a and c axes [18]. In addition, Yb:CALYO crystal has relatively higher specific heat capacity, which means a larger optical damage threshold. A recent investigation on the thermo-optic dispersion formulas of both CALGO and CALYO laser host crystals shows that the thermo-optic properties of CALYO are slightly better than those of CALGO, which makes Yb:CALYO

promising for power scalable lasers [19].The first femtosecond Yb:CALYO oscillator was reported in 2011, delivering 165 fs pulse duration with 740 mW average output power [20]. A Yb:CALYO laser with dssipative soliton operation was also reported with delivering 7.4 ps uncompressed pulses and 340 fs compressed ones [21]. Benefiting from the broad and flat emission spectrum, Pirzio et al. demonstrated Sub-50-fs widely tunable Yb:CALYO laser pumped by single-mode fiber-coupled LD in 2015, generating 43-fs pulses and a wavelength tunability of 40 nm [22]. As short as 33 fs pulses [23] and 30 fs [24] pulses were achieved from a KLM Yb:CALYO oscillator and a passively mode-locked Yb:CALYO oscillator with graphene in 2015 and 2016, respectively. Recently, a record pulse duration of 21 fs was achieved from a KLM Yb:CALYO oscillator [25]. However, due to the restrain of the relative low-brightness and large pump spot of the traditional fiber-coupled laser diodes, the average power in above works were only tens of mW, and the peak power was only in the tens of kW level, which is insufficient in lots of applications.

Generally, the average power of diode-pumped KLM Yb-doped lasers, producing sub-100 fs pulses is mainly restricted by the balance of Kerr effect with mode matching. Because that the Kerr effect strongly depends on the mode radius inside the Kerr medium. However, when using multimode LDs with a large pump spot, it is difficult to obtain a good mode matching as well as a strong Kerr effect. Pumping with single-mode fiber laser with highly brightness is one of the possibilities to overcome this obstacle. Up to 2 W average power with sub-40 fs pulse duration were recently demonstrated from KLM Yb:CALYO oscillator via such a method [26]. However, the average output power was still restrained by the limited available power of single-mode fiber laser. Another effective approach is to separate the gain medium and Kerr medium in a dual-confocal cavity, whose feasibility has already been confirmed in the Kerr-lens mode-locked thin disk lasers [27]. Despite of expensive thin disk lasers, our previous work reported on the proof of concept result of a diode-pumped KLM Yb:CALYO laser based on a dual-confocal cavity [8] delivering 68 fs pulses with 1.5 W average power, which also indicates its potential in power scalable.

Here we further demonstrated a more powerful Kerr-lens mode-locked Yb:CALYO laser at 50 MHz in this method with different kerr media. With a quartz as the Kerr medium, we investigated the output performances of the KLM Yb:CALYO laser with different output couplers (OC). 5.4 W of average output power with 79-fs pulse duration was directly obtained with 15% output coupler (OC). The corresponding single pulse energy and peak power were 108 nJ and 1.2 MW, respectively. Then by using a CaF_2 as the Kerr medium, as short as 59 fs pulses with up to 6.2 W average output power were directly obtained with 15% OC. The corresponding single pulse energy and peak power were 124 nJ and 1.85 MW, respectively. To the best of our knowledge, this is the highest peak power in the sub-100 fs pulse regime that has ever been produced directly from any Yb-ion-doped bulk laser oscillator to date.
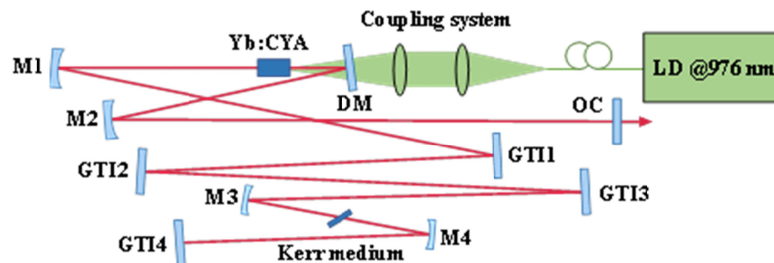
2. Experimental setup

Fig. 1. Experimental setup of the high-power Kerr-lens mode-locked Yb:CALYO laser. M1 and M2: concave mirrors with radius of curvature (ROC) of 300 mm; GTI1-GTI4: Gires-Tournois interferometer mirrors; M3 and M4: concave mirrors with ROC of 100 mm. DM, dichroic mirror; OC: optical coupler.

The schematic of the experimental setup is shown in Fig. 1. The pump laser is a multi-mode fiber coupled diode laser emitting at 976 nm with the maximum output power of 50 W, whose core diameter is 105 μm. In order to realize high-power Kerr-lens mode-locking, a Kerr medium at the Brewster's angle was inserted in the cavity which is similar with the setup in our previous work [8]. However, several improvements are implemented here: firstly, a 6-mm long c-cut 5 at. % doped Yb:CALYO crystal with anti-reflection coating was used to replace the original 2-mm long, 8 at.% doped, uncoated laser crystal. The pump absorption efficiency of this crystal without lasing is 91%. To move the heat accumulation and maintain a stable temperature, the gain crystal was wrapped in indium foil and mounted on heat sink kept at 13 °C. Secondly, we optimized the mode-matching between the pump and laser, so that no hard aperture was needed to realize stable KLM operation. Last but not least, different kinds of Kerr medium not only quartz but also CaF_2 were explored. In addition, three different output couplers (OCs) (2.5%, 5%, 15%) were used in our experiment, which was mounted on a translation stage to start up mode-locking. The dispersion compensation was achieved by using different combinations of several Gires-Tournois interferometer mirrors (GTIs) inside the cavity, with total group delay dispersion (GDD) varies from -1850 fs^2 to -3300 fs^2. And no extra-cavity pulse compression was employed. DM was a dichroic mirror with high reflective for 1 μm laser and high transmittance for pump. The total length of the cavity was about 3 m which corresponds to a repetition rate of 50 MHz.

3. Results and discussion

We firstly characterized the output performances with different output couplers (OCs) using a 2-mm thick quartz as the Kerr medium. With placing the quartz at the Brewster's angle near the center between the M3 and M4, continuous-wave (CW) oscillation started by aligning the laser cavity. For different OCs of 2.5%, 5% and 15%, the maximum CW output powers were 3 W, 6 W and 7.8 W, respectively. The corresponding slope efficiencies were 11.1%, 17.6% and 22.9%, respectively. Then, after finely tuning the position of M4 and the quartz in the cavity, KLM operation was easily realized by fast moving the translation stage of the OC. For each OC, the pulse duration was optimized by fine tuning of the positions of the quartz to adjust the intra-cavity nonlinear phase shift and by managing the negative intra-cavity GDD. The corresponding spectra as well as auto-correlation traces are shown in Figs. 2(a) and 2(b), which were measured by commercial optical spectrum analyzer (AvaSpec-ULS2048, Avantes) and intensity auto-correlator (APE PulseCheck USB), respectively. For 2.5% OC, the central wavelength at CW operation was at 1060 nm and shifted to 1041 nm once mode locked. With a total amount of -3300 fs^2 GDD introduced in the cavity by GTIs, 1.5-W KLM operation was realized. The spectral bandwidth of the spectrum was 11.8 nm which supported a Fourier-limited pulse duration of 96 fs. The FWHM bandwidth of the autocorrelation trace was about 153 fs, corresponding to 99-fs pulse duration if a $sech^2$-pulse shape was assumed. This corresponds to a pulse energy of 30 nJ and a peak power of 270 kW. It is worth to notice that the mode-locking has a Q-switch envelope, which can also tell from the spikes on the spectrum and background on the auto-correlation trace.
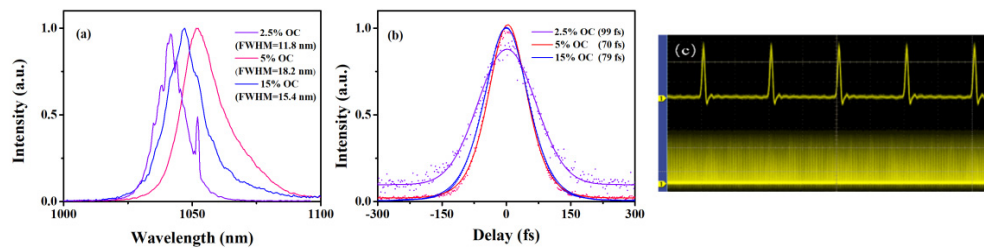
Fig. 2. (a) Mode-locked Spectra for 2.5%, 5% and 15% OCs with optimal dispersion management. (b) Intensity autocorrelation traces for the corresponding pulses, the sech^2-shape fits are shown as solid curves. (c) Mode-locked pulses train trace with 5% OC for 20 ns/div and 2μs/div, respectively.

When using 5% OC, the central wavelength at CW operation was at 1054 nm and shifted to 1052 nm with bandwidth of 18.2 nm at the optimal KLM operation with −2900 fs^2 GDD from GTIs in the cavity. The corresponding auto-correlation trace indicates a pulse duration of 70 fs if a sech^2 pulse shape assumed. The average power in this case was 2.5 W, corresponding to the single pulse energy of 50 nJ and a peak power of 0.63 MW. For 15% OC, the optimal KLM operation was obtained with the GTIs providing −2600 fs^2 GDD. The central wavelength was 1047 nm with a FWHM bandwidth of 15.4 nm, which corresponding to 75-fs transform limited pulse duration. The corresponding auto-correlation trace had a duration at half maximum of 121 fs, results in a pulse duration of 79 fs assuming a sech^2 pulse shape, which is very close to the transform limited pulse duration. The average power in this case was up to 5.4 W, corresponding to the single pulse energy of 108 nJ and the peak power of 1.2 MW, respectively. For the mode-locking with 5% and 15% OCs, they were getting much more stable. As shown in Fig. 2(c), the pulse train of KLM operation with 5% OC was recorded with an oscilloscope with 500 MHz bandwidth, no evidences of Q-switch was observed and the auto-correlation trace in 50 ps time span also shows only one single peak, meaning no multi-pulses operation.
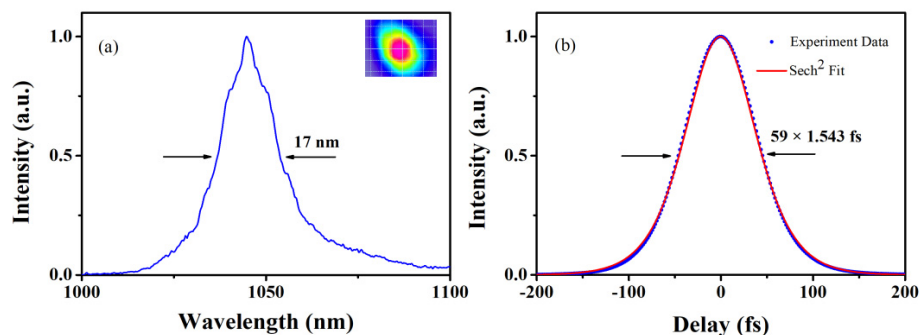

Fig. 3. (a) Laser spectrum of the KLM pulses from the Yb:CYA laser Using CaF$_2$ as Kerr medium. (b) Intensity autocorrelation traces of the pulses, the sech^2-shape fits are shown as red solid curves.

Besides using quartz which has high nonlinear refractive index as Kerr medium, we also investigated the behavior of using a lower nonlinearity Kerr medium of CaF$_2$ with 2-mm thickness. For this case, the maximum CW output power was about 8 W with central wavelength of 1060 nm using 15% OC. By optimizing the position of the CaF$_2$ in the cavity and utilizing a suitable value of round-trip dispersion of −2900 fs^2, as short as 59 fs pulses with as high as 6.2 W average power were directly generated from the oscillator. The mode-locked optical spectrum was centered at 1047 nm with a bandwidth of 17 nm as shown in Fig.

3(a). Via Fourier transform with zero chirp, the transform-limited pulse duration is 50 fs. The corresponding intensity autocorrelation trace was shown in Fig. 3(b). The FWHM bandwidth of the autocorrelation trace was about 91 fs, corresponding to 59 fs pulse duration if a sech^2 pulse shape was assumed, which was close to the Fourier limited pulse duration. The near-field beam profile of the KLM pulses as shown inserted in Fig. 3(a) was a little elliptical because of the astigmatism origin from the four folded concave mirrors. The beam radius along its major and minor axises were 0.63 mm and 0.61 mm, respectively.

To verify the stability of the mode-locking operation, we measured the radio frequency (RF) spectrum using a commercial RF spectrum analyzer (Agilent 4407B). The signal was recorded in a frequency window of 4 MHz with 1 kHz resolution bandwidth (RBW) and 0.6 GHz frequency span with 100 kHz RBW, respectively, as described in Figs. 4(a) and 4(b). The RF spectrum of the fundamental harmonic at 50 MHz had a signal-to-noise ratio of about 83 dBc. No obvious side peaks of the higher orders harmonics were observed, which indicates that the KLM operation was running stably without Q switch instability. The fluctuation of the harmonics peaks in Fig. 4(b) might be originated from the limited sampling rate of the RF spectrum analyzer.
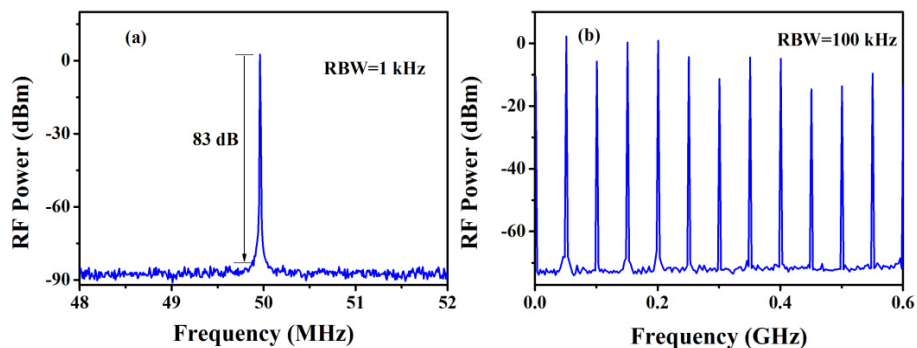

Fig. 4. Radio frequency (RF) spectra at: (a) the fundamental beat note with the resolution bandwidth (RBW) of 1 kHz, and (b) 0.6 GHz wide span range with 100 kHz RBW.

The results in this work were summarized in Fig. 5. As Kerr medium, CaF$_2$ has a better performance than quartz in both pulse duration and average output power during our experiment, which is due to the less nonlinear phase. The KLM operations were easily started and able to last hours once been realized. No evidences of saturation effects or thermal degradation were observed. Our results are compared with other Yb-doped lasers generating sub-100 fs pulses with >5 W output power with both bulk and thin-disk geometries in Fig. 6, which was previously only achieved from Yb:Lu$_2$O$_3$ [28,29], Yb:CALGO [1,30] and Yb:LuScO$_3$ [31] crystals. It can be seen that there is no previous work reporting on generating pulses with >6 W average power as well as <60 fs pulse duration. In addition, for the region with >100 nJ pulse energy or >1 MW peak power with sub-100 fs pulse duration, there were only results based on Yb:CALGO bulk laser as well as Yb:Lu$_2$O$_3$ thin-disk laser before. Although, the TDL has the advantage in thermal management, it has also more complex pumping system. In this work, we reported comparable results from the Yb:CALYO crystal, with up to 1.85-MW peak power, which shows the advantages in high-power sub-100 fs pulses generation of such Yb-doped calcium aluminate crystals. It will push people to develop and investigate new materials belongs to this family for better performances in ultra-fast, ultra-intense lasers.
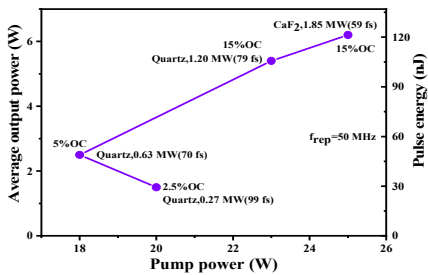
Fig. 5. Output power and pulse energy for different OCs and Kerr medium versus pump power.
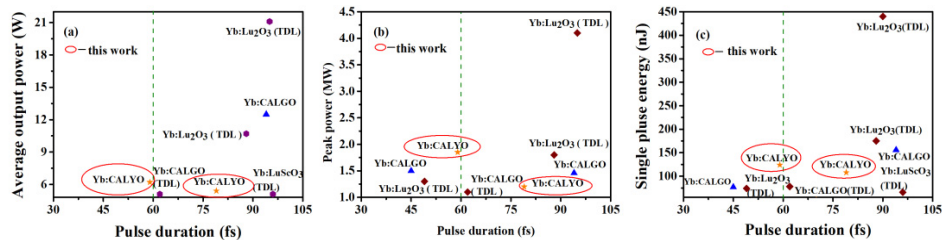

Fig. 6. Comparison of the (a) average power, (b) peak power and (c) single pulse energy with other Yb-based solid-state lasers generating sub-100 fs pulses with >5 W output power [1,3,28–31].TDL: thin disk laser.

4. Conclusion

In conclusion, we have studied on the output performances from a diode-pumped high power KLM Yb:CALYO laser with different Kerr-medium. When using a 2-mm thick quartz, the KLM Yb:CALYO laser directly produced 79 fs pulses with 5.4 W of average output power with 15% OC and 70 fs pulses with 2.5 W of average power with 5% OC. When using a CaF_2 crystal as the Kerr medium, as short as 59 fs pulses with as high as high as 6.2 W average power were directly generated from the oscillator, which is the highest average power for the sub-60 fs Yb-doped solid-state lasers. The repetition rate of the KLM Yb:CALYO laser was 50 MHz, resulting in the maximum of 124-nJ single pulse energy and 1.85-MW peak power, which is also the highest peak power ever achieved from any sub-100 fs Yb-doped bulk oscillators. Taking into consideration of high nonlinear reflective index of Yb:CALYO crystal, diode-pumped Kerr-lens mode-locked oscillator with dual-crystal and dual-confocal cavity aiming higher output power with sub-100-fs pulse duration is under implement.

References

1. 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 (2002).
2. 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**(20), 6001–6004 (2014).
3. S. Manjooran and A. Major, "Diode-pumped 45 fs Yb:CALGO laser oscillator with 1.7 MW of peak power," Opt. Lett. **43**(10), 2324–2327 (2018).
4. P. Sévillano, R. Dubrasquet, F. Druon, P. Georges, D. Descamps, and E. Cormier, "37 fs - 1.5 W Kerr-lens mode-locked Yb:CALGO laser oscillator," in *Conference on Lasers and Electro-Optics* (Optical Society of America, 2014), paper STu2E.1.

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**(11), 2321–2325 (2015).

6. 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**(20), 4008–4010 (2013).

7. P. Sévillano, G. Machinet, R. Dubrasquet, P. Camy, J.-L. Doualan, R. Moncorgé, P. Georges, F. Druon, D. Descamps, and E. Cormier, "Sub-50 fs, Kerr-lens mode-locked Yb:CaF2 laser oscillator delivering up to 2.7 W," in *Advanced Solid-State Lasers Congress* (Optical Society of America, 2013), paper AF3A.6.

8. W. Tian, Y. Peng, Z. Zhang, Z. Yu, J. Zhu, X. Xu, and Z. Wei, "Diode-pumped power scalable Kerr-lens mode-locked Yb:CYA laser," Photon. Res. **6**(2), 127–131 (2018).

9. H. Zhao and A. Major, "Megawatt peak power level sub-100 fs Yb:KGW oscillators," Opt. Express **22**(25), 30425–30431 (2014).

10. R. Akbari, H. Zhao, K. A. Fedorova, E. U. Rafailov, and A. Major, "Quantum-dot saturable absorber and Kerr-lens mode-locked Yb:KGW laser with >450 kW of peak power," Opt. Lett. **41**(16), 3771–3774 (2016).

11. H. Zhao and A. Major, "Powerful 67 fs Kerr-lens mode-locked prismless Yb:KGW oscillator," Opt. Express **21**(26), 31846–31851 (2013).

12. R. Akbari, K. A. Fedorova, E. U. Rafailov, and A. Majo, "Diode-pumped ultrafast Yb:KGW laser with 56 fs pulses and multi-100 kW peak power based on SESAM and Kerr-lens mode locking,"," Appl. Phys. B **123**(4), 123 (2017).

13. W. Tian, J. Zhu, Y. Peng, Z. Wang, L. Zheng, L. Su, J. Xu, and Z. Wei, "High power sub 100-fs Kerr-lens mode-locked Yb:YSO laser pumped by single-mode fiber laser," Opt. Express **26**(5), 5962–5969 (2018).

14. 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).

15. 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**(4), 2904–2909 (2011).

16. S. Kitajima, H. Nakao, A. Shirakawa, H. Yagi, and T. Yanagitani, "Kerr-lens mode-locked Yb^{3+}-doped Lu$_3$Al$_5$O$_{12}$ ceramic laser," Opt. Lett. **41**(19), 4570–4573 (2016).

17. 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).

18. D. Li, X. Xu, H. Zhu, X. Chen, W. D. Tan, J. Zhang, D. Tang, J. Ma, F. Wu, C. Xia, and J. Xu, "Characterization of laser crystal Yb:CaYAlO$_4$," J. Opt. Soc. Am. B **28**(7), 1650–1654 (2011).

19. 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**(12), 2275–2278 (2017).

20. W. D. Tan, D. Y. Tang, X. D. Xu, D. Z. Li, J. Zhang, C. W. Xu, and J. Xu, "Femtosecond and continuous-wave laser performance of a diode-pumped Yb^{3+}:CaYAlO$_4$ laser," Opt. Lett. **36**(2), 259–261 (2011).

21. W. D. Tan, D. Y. Tang, C. W. Xu, J. Zhang, X. D. Xu, D. Z. Li, and J. Xu, "Evidence of dissipative solitons in Yb^{3+}:CaYAlO$_4$," Opt. Express **19**(19), 18495–18500 (2011).

22. F. Pirzio, S. D. 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**(8), 9790–9795 (2015).

23. 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**(6), 335–338 (2015).

24. 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:CaYAlO4 laser," Opt. Lett. **41**(5), 890–893 (2016).

25. J. Ma, X. Xu, D. Shen, and D. Tang, "21-fs Kerr-lens Mode-locked Yb:CaYAlO$_4$ Laser," *in Conference on Lasers and Electro-Optics* (Optical Society of America, 2018), paper JTh2A.158.

26. W. Tian, J. Zhu, Z. Wang, X. Xu, J. Xu, and Z. Wei, "Sub-40 fs, 2 W Kerr-lens mode-locked Yb:CYA laser," in *Laser Congress 2018 (ASSL)* (Optical Society of America, 2018), paper ATh2A.5.

27. J. Brons, V. Pervak, E. Fedulova, D. Bauer, D. Sutter, V. Kalashnikov, A. Apolonskiy, O. Pronin, and F. Krausz, "Energy scaling of Kerr-lens mode-locked thin-disk oscillators," Opt. Lett. **39**(22), 6442–6445 (2014).

28. C. Paradis, N. Modsching, V. J. Wittwer, B. Deppe, C. Kränkel, and T. Südmeyer, "Generation of 35-fs pulses from a Kerr lens mode-locked Yb:Lu$_2$O$_3$ thin-disk laser," Opt. Express **25**(13), 14918–14925 (2017).

29. N. Modsching, J. Drs, J. Fischer, C. Paradis, F. Labaye, M. Gaponenko, C. Kränkel, V. J. Wittwer, and T. Südmeyer, "Sub-100-fs Kerr lens mode-locked Yb:Lu$_2$O$_3$ thin-disk laser oscillator operating at 21 W average power," Opt. Express **27**(11), 16111–16120 (2019).

30. A. Diebold, F. Emaury, C. Schriber, M. Golling, C. J. Saraceno, T. Südmeyer, and U. Keller, "SESAM mode-locked Yb:CaGdAlO$_4$ thin disk laser with 62 fs pulse generation," Opt. Lett. **38**(19), 3842–3845 (2013).

31. C. J. Saroceno, O. H. Heckl, C. R. E. Baer, C. Schriber, M. Golling, K. Beil, C. Krankel, T. Sudmeyer, G. Huber, and U. Keller, "Sub-100 femtosecond pulses from a SESAM mode-locked thin disk laser," Appl. Phys. B **106**(3), 559–562 (2012).