260-megahertz, megawatt-level thin-disk oscillator

Jinwei Zhang,[1,2] Jonathan Brons,[1] Nikolai Lilienfein,[1] Elena Fedulova,[1] Vladimir Pervak,[3] Dominik Bauer,[4] Dirk Sutter,[4] Zhiyi Wei,[2] Alexander Apolonski,[1,3] Oleg Pronin,[3,*] and Ferenc Krausz[1,3]

[1]*Max-Planck-Institute of Quantum Optics, Hans-Kopfermann-Str. 1, 85748 Garching, Germany*

[2]*Beijing National Laboratory for Condensed Matter Physics and Institute of Physics, Chinese Academy of Sciences, Beijing 100190, China*

[3]*Ludwig-Maximilians-University Munich, Am Coulombwall 1, 85748 Garching, Germany*

[4]*TRUMPF-Laser GmbH and Co. KG, Aichhalder Straße 39, 78713 Schramberg, Germany*

**Corresponding author: oleg.pronin@mpq.mpg.de*

Received December 4, 2014; revised March 10, 2015; accepted March 12, 2015;
posted March 13, 2015 (Doc. ID 229052); published April 3, 2015

A Kerr-lens mode-locked (KLM) Yb:YAG thin-disk oscillator delivering 215-fs pulses with 75-W average power and 1.4-MW peak power at a repetition rate of 260 MHz is presented. Self-starting KLM is demonstrated at an output power of 68 W. This is the highest repetition rate of any mode-locked thin-disk oscillators so far. Concepts for scaling the repetition rate up to 1 GHz are discussed.

OCIS codes: (140.4050) Mode-locked lasers; (140.7090) Ultrafast lasers; (140.3580) Lasers, solid-state; (140.3480) Lasers, diode-pumped.

http://dx.doi.org/10.1364/OL.40.001627

Highest peak powers directly from laser oscillators rely on diode-pumped solid-state thin-disk (TD) laser technology [1]. Mode-locked Yb:YAG thin-disk lasers permitted the generation of sub-picosecond pulses at unprecedented average and peak power levels in the multi-100-W average power and near-100-MW peak power range, respectively [2–5], thus paving the way to a new third-generation femtosecond technology [6]. The peak power of mode-locked oscillators can be scaled via reducing the repetition rate and/or increasing average power [2–5]. By contrast, the power delivered per mode, highly relevant in frequency-domain metrology [7], can be maximized by increasing the repetition rate. To date, the highest repetition rate of a mode-locked thin-disk oscillator is 81 MHz [8], and no attempt was reported to scale this repetition rate toward the GHz frontier. The combination of high average power (> 100 W) and high repetition rate (> 200 MHz) is of interest for a number of applications, including the development of compact sources of coherent radiation all the way from the mid-infrared to the extreme ultraviolet (via nonlinear frequency conversion), with particular emphasis for UV-XUV and MIR frequency-comb spectroscopy [9–11]. The enhanced power per mode implies an improved signal-to-noise (S/N) ratio in optical-frequency metrology and frequency-comb spectroscopy [12]. Femtosecond enhancement cavities [13,14] also benefit from such a compact front end with high average power and repetition rate due to relaxed demand on the cavity *Q*-factor and to the more compact setup and resultant mechanical stability.

The first KLM thin-disk oscillator was demonstrated in 2011 generating 200-fs and 270-fs pulses at energy levels of 0.4 μJ and 1.1 μJ, respectively, at a 40-MHz repetition rate [15]. Recently, such a system has been scaled up to 38-MW peak and 270-W average power, the highest values to date for oscillators operating in ambient air [5]. Capitalizing on these two previous experiments, in this Letter, we report on a KLM thin-disk Yb:YAG oscillator delivering 215-fs pulses at an average power level of 75 W and a repetition rate of 260 MHz.

Initially, the laser oscillator with a cavity length of 1.5 m was realized to yield a repetition rate of 100 MHz. The experimental setup is shown in Fig. 1(a) with a thin (≈ 1/10 mm) wedged Yb:YAG disk with a concave radius of curvature of about 20 m and a multi-pass pump cavity generating a pump spot diameter of 2.5 mm (TRUMPF

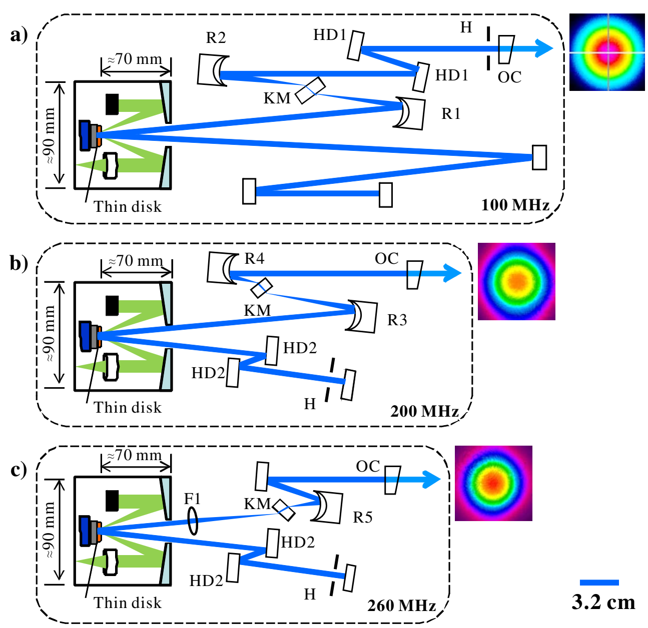

Fig. 1. Schematics of the KLM thin-disk Yb:YAG oscillator realized at a repetition rate of (a) 100 MHz, (b) 200 MHz, and (c) 260 MHz, along with their output beam profiles (insets). The distances between resonator elements are to scale. All flat mirrors are highly reflective; HD1 and HD2, high-dispersion mirrors with a group-delay dispersion of approximately −3000 fs^2 and −2000 fs^2 per bounce, respectively; OC, output coupler with 10% transmission; R1-R3 and R4-R5, concave spherical mirrors with a radius of curvature of 150 mm and 50 mm, respectively; F1, convex lens with a focal length of 75 mm; KM, Kerr medium, 1-mm sapphire plate positioned at Brewster's angle at the beam waist; H, hard aperture with a diameter of 2.2 mm.

Laser GmbH). The disk is used as one of the folding mirrors in a Z-shaped cavity. It is pumped by a fiber-coupled diode laser at 940 nm. The cavity is slightly asymmetric relative to the position of Kerr medium (KM). The disk is placed in one of the cavity arms exhibiting a beam diameter of 2.2 mm on the disk (defined as $1/e^2$ of intensity maximum). A 1-mm-thick sapphire plate is used as a nonlinear Kerr medium at the beam waist of a diameter of 45 μm. With an output coupler of 10%, the oscillator delivered 250-fs pulses [assuming a sech^2 pulse shape, see Fig. 2(a)] centered at 1030 nm with a beam quality of $M^2 \approx 1.1$. The average power is 90 W at 470-W pump power corresponding to an optical-to-optical efficiency of 19%. The oscillator was enclosed in a robust water-cooled housing, sealed to prevent air flow and external environmental influences. These engineering efforts resulted in an excellent intensity stability of <0.3% (root mean square, rms) over the bandwidth from 1 Hz to 200 MHz, beam-pointing stability of better than 2 μrad (rms deviation), and unattended operation over the full day.

The main challenge in increasing the repetition rate and average power simultaneously is posed by the conflicting requirements of short cavity length and large beam size on the disk, respectively. The power scaling concept of the TD geometry implies enlargement of the beam diameter on the TD crystal with increased pump power. Depending on the pump wavelength (940 nm or 969 nm for Yb:YAG) implying a different quantum defect, the maximum pump power density applicable varies in the range of 8–12 kW/cm^2. This requires pump beam

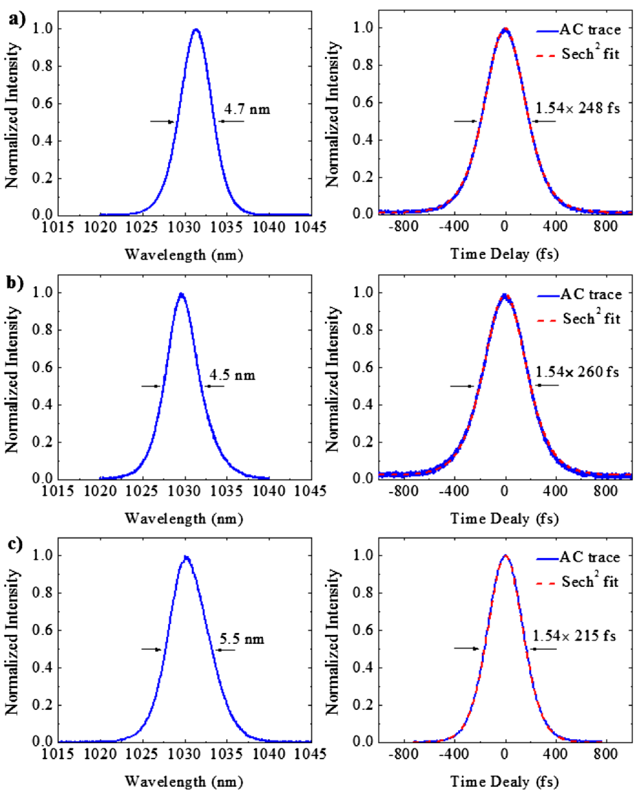

Fig. 2. Spectra and pulse durations of the KLM Yb:YAG oscillator depicted in Fig. 1 at a repetition rate of (a) 100 MHz, (b) 200 MHz, and (c) 260 MHz.

diameters of several millimeters for a 100-W-class KLM laser taking into account an efficiency of about 25% [15]. However, shortening the cavity tends to reduce the intracavity beam size [16], deteriorating the overlap between the resonator mode and the pump beam and thereby the optical-to-optical efficiency. For example, in a symmetric confocal resonator consisting of two concave mirrors with radius of curvature R and separated by the distance L ($L = R$), the mode radius at the mirrors scale as $\omega = \sqrt{\lambda L/\pi}$. Moreover, geometric constraints set a lower limit to the distance between the disk and a neighboring optical element at about 70 mm, dictated by the multipass pumping configuration (see Fig. 1).

Possible solutions to the difficulties described above include (i) a strongly asymmetric resonator and/or (ii) a single pass (per round-trip) through the disk. Approach (i) can be realized with two concave mirrors of different radii of curvature. The resulting cavity is asymmetric with strongly differing beam sizes in the two cavity arms [17,18]. In contrast to [17,18], the oscillator presented here has the gain medium separated from the Kerr medium, which on the one hand grants more freedom in optimizing the oscillator power, but on the other hand increases the complexity of the oscillator. This is opposed to the typical KLM oscillators operating with only a soft-aperture and a combined gain and Kerr medium. Additionally, due to the complex spatio-temporal dynamics of the Kerr-lens regime and the correspondingly complex numerical simulations, it is also hard to predict the peak power level of the oscillator, especially when a non-standard asymmetric cavity configuration is chosen. Our previous experiment on power scaling concepts of KLM thin-disk oscillators [5] utilized symmetric cavity configurations and could not be straightforwardly used to predict peak power levels of non-standard asymmetric resonator configurations. One of the cavity arms spans the distance from the output coupler to the focal point within the KM, and the second cavity arm spans the remainder of the cavity (see Fig. 1). This strongly asymmetric configuration reconciles, to some extent, the inconvenience of arrangement due to the short cavity length and the extension of the TD module (incl. pump optics). In Fig. 1, the disk is used as one of the folding mirrors. Approach (ii) may be considered to trade off the round-trip gain against repetition rate and appears to be a must if repetition rates above 300 MHz are to be achieved with the commercial thin-disk laser module employed.

Based on this analysis, in a second experimental step, a strongly asymmetric configuration was used to further increase the repetition rate up to 200 MHz. The setup is illustrated in Fig. 1(b). The radii of the two concave mirrors are 150 mm and 50 mm, respectively. This results in a larger mode size in the cavity arm containing mirror R3. The beam is well collimated in this arm, meaning that the beam size on the output coupler and the disk are almost the same. Furthermore, shortening or increasing the length of this arm does not have any pronounced influence on the beam size and divergence. The TD is placed in this arm to enable a beam size well matched to that of the pump beam of a diameter of 2.5 mm. As a consequence, the beam size in the other cavity arm decreases to a beam diameter of 160 μm on the OC. The dispersive mirrors are placed in the arm with larger beam size in order to avoid damage caused by the high intensities during the oscillator start-up. 75 W of average output power under 315-W pump power was achieved with an output coupler of 10%, corresponding to an optical-to-optical efficiency of 24%. The spectral width is 4.5 nm, and the pulse duration is 260 fs [see Fig. 2(b)]. The pulse energy and the peak power are 0.38 μJ and 1.4 MW, respectively.

A further increase in repetition rate made a replacement of the 150-mm concave mirror [R3 in Fig. 1(b)] with a 75-mm lens [F1 in Fig. 1(c)] necessary. This measure shortens the distance between the TD module and the first concave mirror and simultaneously decreases intracavity astigmatism caused by the large folding angle of the concave mirror. The lens could be placed directly in front of the TD module, considerably shortening the distance from the disk to the lens. By this approach, the cavity length was decreased down to 577 mm, yielding a repetition rate of 260 MHz. The corresponding setup is shown in Fig. 1(c). The size of the entire 260-MHz cavity is now comparable to the size of the TD module. This oscillator provides 75-W average power and 0.3-μJ pulse energy with an optical-to-optical efficiency of 21.4%. The spectrum and the intensity autocorrelation are shown in Fig. 2(c), exhibiting a pulse duration of 215 fs. The beam size in the KM stayed the same as in the 200-MHz oscillator, so the fact that the peak power stayed constant with differing GDD should not come as a surprise.

All oscillator configurations described (see Table 1) can operate in the self-starting KLM regime, however, with somewhat reduced power. This mode of operation yields an average output power of 68 W, 56 W, and 53 W for the 100-MHz, 200-MHz, and 260-MHz oscillators, respectively. Self-starting was achieved by optimizing the position of the KM relative to the beam focus. After blocking the beam inside the cavity and unblocking it again, mode-locking immediately resumes. The KM can be moved away from this optimal self-starting position. In this case, the oscillator output power can be increased at simultaneously increased pump power (see Table 1). The maximum 90-W, 75-W, and 75-W average power levels were obtained in that non-self-starting mode-locked regime. Mode-locking in this latter case needs to be initiated by gentle translation of the output coupler mirror.

Table 1. Summary of the Parameters of Different Repetition-Rates Thin Disk Oscillators[a]

f_{rep} (MHz)	100	200	260
Pump λ (nm)	940	940	940
P_{avg} (W)	90	75	75
E_P (μJ)	0.9	0.38	0.3
P_{peak} (MW)	3.6	1.4	1.4
τ (fs)	248	260	215
GDD (fs^2)	−6000	−8000	−5500
η_{O-O}	19%	24%	21.4%

[a] f_{rep}, repetition rate; pump λ, pump wavelength; P_{avg}, average power; E_P, pulse energy; P_{peak}, peak power; τ, pulse duration; GDD, intra-cavity dispersion; η_{O-O}, optical-to-optical efficiency.

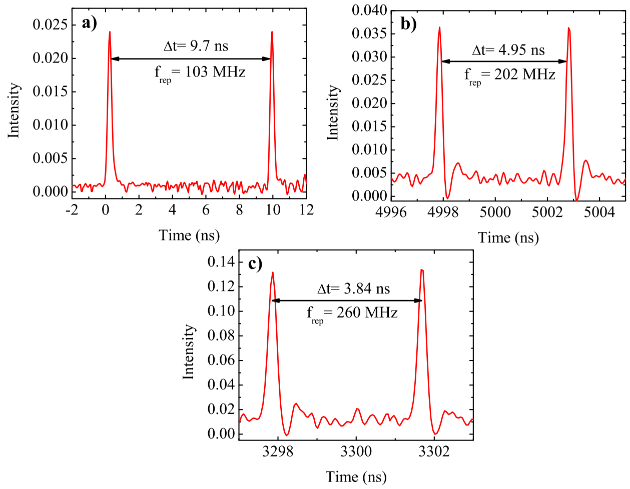

Fig. 3. Sampling oscilloscope measurement of different oscillators (a) with pulse separation of 9.7 ns, corresponding to a repetition rate of 100 MHz, (b) with pulse separation of 4.95 ns, corresponding to a repetition rate of 200 MHz, (c) with pulse separation of 3.84 ns, corresponding to a repetition rate of 260 MHz.

A fast photodiode (bandwidth >5 GHz) and an oscilloscope with 3.5-GHz bandwidth were used to confirm a single-pulse operation in the range of 500 ps$^{-1}/f_{\mathrm{rep}}$ (see Fig. 3). Additionally, a homemade autocorrelator was used to confirm single pulses in the range 0–500 ps.

To further increase the repetition rate, a resonator with even stronger asymmetry will be necessary to preserve a pump beam size of 2.5 mm on the disk. Also, a single-pass configuration with the TD placed as an end mirror is needed. Our experiments along with these considerations suggest that a repetition rate of about 0.5 GHz can be reached in the near future. Approaching or even surpassing the 1-GHz frontier, however, would require a side-pumped thin-disk geometry [19], which does not have strict spatial constrains on placing the neighboring optical elements closer to the disk. Thanks to the high peak power that will be maintained up to the 1-GHz regime, carrier-envelope phase stabilization, and extracavity pulse compression are expected to be achievable in a similar way as demonstrated earlier in the sub-100-MHz regime [20,21].

In conclusion, we have demonstrated thin-disk oscillators spanning the range of output powers from 75 to 100 W and repetition rates from 100 to 260 MHz (see Table 1). We have shown that a strongly asymmetric geometry of the KLM resonator offers nearly the same performance as the symmetric configuration while helping scale the repetition rate in the high-power regime. Additionally to this, the oscillator can be easily started and even self-started at slightly lower output power. A next milestone of 0.5 GHz appears to be feasible with an even more asymmetric resonator configuration and the thin-disk implemented as one of the resonator end mirrors.

This work was supported by the Munich Centre for Advanced Photonics (MAP) and the International Joint Research Programme of National Natural Science Foundation of China (grant no. 61210017).

References

1. A. Giesen, H. Hügel, A. Voss, K. Wittig, U. Brauch, and H. Opower, Appl. Phys. B **58**, 365 (1994).
2. D. Bauer, I. Zawischa, D. H. Sutter, A. Killi, and T. Dekorsy, Opt. Express **20**, 9698 (2012).
3. C. J. Saraceno, F. Emaury, C. Schriber, M. Hoffmann, M. Golling, T. Südmeyer, and U. Keller, Opt. Lett. **39**, 9 (2014).
4. A. A. Eilanlou, Y. Nabekawa, M. Kuwata-Gonokami, and K. Midorikawa, Jpn. J. Appl. Phys. **53**, 082701 (2014).
5. J. Brons, V. Pervak, E. Fedulova, D. Bauer, D. Sutter, V. Kalashnikov, A. Apolonskiy, O. Pronin, and F. Krausz, Opt. Lett. **39**, 6442 (2014).
6. H. Fattahi, H. G. Barros, M. Gorjan, T. Nubbemeyer, B. Alsaif, C. Y. Teisset, M. Schultze, S. Prinz, M. Haefner, M. Ueffing, A. Alismail, L. Vámos, A. Schwarz, O. Pronin, J. Brons, X. T. Geng, G. Arisholm, M. Ciappina, V. S. Yakovlev, D. E. Kim, A. M. Azzeer, N. Karpowicz, D. Sutter, Z. Major, T. Metzger, and F. Krausz, Optica **1**, 45 (2014).
7. T. Udem, R. Holzwarth, and T. W. Hänsch, Nature **416**, 233 (2002).
8. C. Baer, C. Kränkel, C. Saraceno, O. Heckl, M. Golling, T. Südmeyer, R. Peters, K. Petermann, G. Huber, and U. Keller, Opt. Lett. **34**, 2823 (2009).
9. C. Gohle, T. Udem, M. Herrmann, J. Rauschenberger, R. Holzwarth, H. A. Schuessler, F. Krausz, and T. W. Hänsch, Nature **436**, 234 (2005).
10. A. Schliesser, N. Picqué, and T. W. Hänsch, Nat. Photonics **6**, 440 (2012).
11. I. Pupeza, D. Sanchez, O. Pronin, J. Zhang, N. Lilienfein, M. Seidel, I. Znakovskaya, V. Pervak, Z. Wei, and F. Krausz, *CLEO: 2014 Postdeadline Paper Digest*, OSA Technical Digest (online) (Optical Society of America, 2014), paper STh5C.7.
12. A. Bartels, R. Gebs, M. S. Kirchner, and S. A. Diddams, Opt. Lett. **32**, 2553 (2007).
13. R. J. Jones, K. D. Moll, M. J. Thorpe, and J. Ye, Phys. Rev. Lett. **94**, 193201 (2005).
14. I. Pupeza, S. Holzberger, T. Eidam, H. Carstens, D. Esser, J. Weitenberg, P. Russbüldt, J. Rauschenberger, J. Limpert, T. Udem, A. Tünnermann, T. W. Hänsch, A. Apolonski, F. Krausz, and E. Fill, Nat. Photonics **7**, 608 (2013).
15. O. Pronin, J. Brons, C. Grasse, V. Pervak, G. Boehm, M.-C. Amann, V. Kalashnikov, A. Apolonski, and F. Krausz, Opt. Lett. **36**, 4746 (2011).
16. N. Hodgson and H. Weber, *Laser Resonators and Beam Propagation*, 2nd ed. (Springer, 2005), p. 238
17. S. Uemura and K. Miyazaki, Opt. Commun. **138**, 330 (1997).
18. A. Lytle, E. Gershgoren, R. Tobey, M. Murnane, H. Kapteyn, and D. Müller, Opt. Express **12**, 1409 (2004).
19. T. Yanagisawa, S. Yamamoto, and Y. Hirano, *Advanced Solid-State Photonics*, OSA Technical Digest (Optical Society of America, 2004), paper WA1.
20. O. Pronin, M. Seidel, J. Brons, F. Lücking, V. Pervak, A. Apolonski, T. Udem, and F. Krausz, *Advanced Solid-State Lasers Congress*, G. Huber and P. Moulton, eds., OSA Technical Digest (online) (Optical Society of America, 2013), paper AF3A.5.
21. M. Seidel, O. Pronin, J. Brons, E. Fedulova, F. Lücking, I. Angelov, V. Pervak, A. Apolonski, and F. Krausz, *Advanced Solid-State Lasers Congress*, G. Huber and P. Moulton, eds., OSA Technical Digest (online) (Optical Society of America, 2013), paper ATu4A.7.