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Research Article

Distributed Kerr Lens Mode-Locked Yb:YAG Thin-Disk Oscillator

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Ultrafast laser oscillators are indispensable tools for diverse applications in scientific research and industry. When the phases of the longitudinal laser cavity modes are locked, pulses as short as a few femtoseconds can be generated. As most high-power oscillators are based on narrow-bandwidth materials, the achievable duration for high-power output is usually limited. Here, we present a distributed Kerr lens mode-locked Yb:YAG thin-disk oscillator which generates sub-50 fs pulses with spectral widths far broader than the emission bandwidth of the gain medium at full width at half maximum. Simulations were also carried out, indicating good qualitative agreement with the experimental results. Our proof-of-concept study shows that this new mode-locking technique is pulse energy and average power scalable and applicable to other types of gain media, which may lead to new records in the generation of ultrashort pulses.

1. Introduction

Over the last decades, the progress on the development of ultrafast oscillators has been subject to intensive research driven by diverse applications in physics, biology, chemistry, medicine, and industry [1–4]. Passive mode locking has been the most effective method for generating ultrashort pulses from laser oscillators [5–10]. Despite the widespread commercial availability of mode-locked lasers, research on new mode-locking techniques is still ongoing. This quest is primarily driven by the desire for a universal technique that is applicable across different laser types and one that can generate the shortest possible pulse. In addition, the dynamics and formation of dissipative solitons in mode-locked oscillators are themselves interesting research topics, owing to the insight they may provide into diverse areas such as field theory, cosmology, optics, condensed matter physics, and even life sciences [11]. In the past decades, a few methods were used to generate ultrashort pulses directly from passive mode-locked oscillators, such as using broadband gain material [12–14], improving dispersion management [15], and introducing spectral filtering [16]. Yet the pulse duration achievable is still limited by the emission bandwidth of the gain medium. In 1975, Haus [17] showed that the complex Ginzburg-Landau equation, used for modelling the behavior of mode-locked oscillators, can be solved analytically if one assumes the presence of a fast saturable absorber and a Gaussian gain profile, and neglects the saturation dynamics of the mode locker. According to it, the pulse duration scales as

$$t = \frac{1}{\Omega_g}\sqrt{\frac{l}{\kappa}}, \quad (1)$$

where Ω_g is the full-width-at-half-maximum (FWHM) gain bandwidth, l is the linear loss the laser pulse suffers upon one round trip in the resonator, and κ is the modulation depth, often referred to as the self-amplitude modulation (SAM) coefficient of the mode locker. Equation (1) implies that the steady-state mode-locked laser spectrum can overcome the gain bandwidth for a sufficiently low linear loss and high nonlinear modulation depth. Under these conditions, the steady-state pulse continuously extracts energy from the gain medium and redistributes it to the wings of its spectrum where net gain is absent.

Reduction of the linear loss has already been demonstrated to result in shorter pulse durations [18–20]. This procedure naturally implies very low output powers, supporting the general belief that the achievable pulse duration is limited by the bandwidth of the gain medium. An alternative approach is to increase the modulation depth κ of the mode locker. It has been demonstrated in bulk-crystal mode-locked oscillators [21–24], enabling the generation of pulses with broader spectrum and shorter pulse duration. However, these results have not shown a significant extension of the generated spectrum beyond the gain spectrum bandwidth. Besides, the thermal effects of the bulk gain media restrict their output powers at a very low level.

Compared to the bulk crystal oscillator, thin-disk technology has been one of the most promising concepts for power and energy scaling ever since its first demonstration in 1994 [25]; the thin thickness (<200 μm) and relatively large diameter (~10 mm) of the disk crystal enable fast and one-dimensional heat removal along the optical axis of the resonator, minimizing the transversal temperature gradient and the phase distortions transversal to the laser beam thus allowing extremely high pump power densities. Yb:YAG is the most widely used thin-disk crystal due to its outstanding properties. Power levels of several hundred watts and peak powers of more than 40 MW have been delivered directly from mode-locked Yb:YAG thin-disk oscillators [26–29]. Recently, Fischer et al. realized 105 fs pulses from a Yb:YAG thin-disk oscillator with intracavity average power of 470 W, which was used for intra-oscillator high harmonic generation [30]. They further obtained 69 W pulses with pulse duration of 84 fs by adopting a regime of strong self-phase modulation (SPM) in the Yb:YAG thin-disk laser [31]. In a low-pressure environment, nearly 100 MW peak power has been achieved from a Yb:YAG thin-disk oscillator with an average power of 220 W and pulse duration of 140 fs [32].

Here, we demonstrate a distributed Kerr lens mode-locking (DKLM) technique in a Yb:YAG thin-disk oscillator. It is comprised of multiple Kerr lenses and extends the widely used and powerful method of Kerr lens mode locking (KLM) [9], significantly increasing the SAM coefficient for KLM. The mode-locked spectrum (FWHM) exceeds the emission bandwidth of the Yb:YAG gain medium by a factor of ≈4, leading to 47 fs pulses generated directly from the oscillator. Moreover, in discrete cavity configurations, nearly continuous tuning from sub-50 fs to 200 fs pulse durations with average output powers ranging from a few watts up to 53 W from the single oscillator was demonstrated.

2. Materials and Methods

Our experiments were carried out in a KLM Yb:YAG thin-disk oscillator operating at a repetition rate of 203 MHz [33]. The original oscillator delivered 260 fs pulses at the central wavelength of 1030 nm with an average power of 75 W. A sapphire plate was placed in the focus of the telescope section as the Kerr medium, which separated the beam into two arms (see arm 1 and arm 2 in Figure 1). It provided the necessary self-focusing effect and SAM in the presence of an intracavity aperture to initiate Kerr lens mode locking. The strength of the SAM coefficient dictates the pulse formation [34] and the final pulse duration. To enhance the total SAM, additional nonlinear plates were inserted at the Brewster angle near the end of arm 1, where the beam diameter, at around 200 μm, was significantly smaller compared to that of arm 2 (see Supplementary Figure 6). They were put very close to the OC with a distance of about 4 mm between each other. The set of nonlinear plates acted as distributed Kerr lenses, greatly enhancing the SAM effect of the original Kerr medium. With the distributed Kerr lenses, the nonlinearity and modulation depth can be gradually increased. Since the beam diameter changed much more smoothly compared to that at the focus between R1 and R2, the introduced Kerr lens effect increased, to a certain extent, proportionally with the thickness and numbers of the plates. In contrast to previous demonstrations [18, 21, 22], this approach appears to increase the overall modulation depth, allowing the oscillator to tolerate the high intracavity nonlinearity introduced by the same lenses and undesirable effects such as multiple pulsing.

3. Results and Discussion

The nonlinear Kerr plates were successively introduced in arm 1, starting with plate C1 and ending with plate C6. The distance of the telescope section and position of the KM were adjusted in order to initiate and optimize mode locking when each additional plate was inserted. With more plates added, the mode locking tended to operate more close to the edge of the stability zone of the cavity. Together with the optimization of the roundtrip group delay dispersion (GDD) and the output coupling ratio, the pulse duration was gradually shortened. The thickness of the KM was increased to 2 mm with more than two nonlinear plates inserted in order to ease the initiation of mode locking. As a result, 145 fs pulses (at average power of 40 W), 80 fs pulses (at average power of 17 W), and 65 fs pulses (at average power of 8 W) were generated, respectively. The output spectrum was also gradually broadened beyond the emission

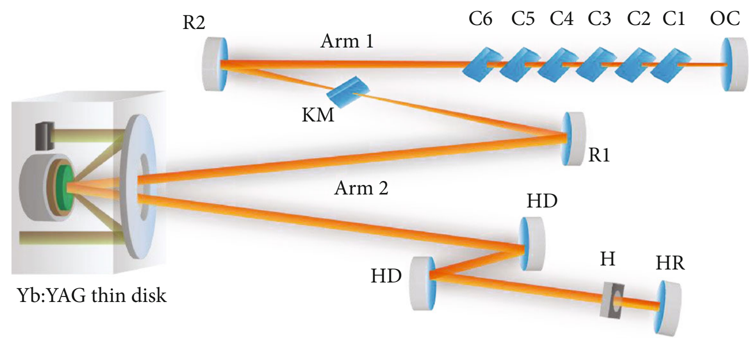

FIGURE 1: Schematic representation of the DKLM Yb:YAG thin-disk oscillator. A wedged Yb:YAG thin disk with a thickness of ~0.1 mm and a ROC of -20 m was used as the gain medium. It was placed inside a 36-pass pump cavity as a folding mirror and pumped by a fiber-coupled diode laser at 940 nm. The resulting pump beam size on the disk was 2.5 mm in diameter. A set of nonlinear plates were inserted close to the OC, including one YAG plate (C1, 3 mm thick, $n_2 \approx 6.3 \times 10^{-16}$ cm^2/W) and five sapphire plates (C2-C6, 3 mm thick, $n_2 \approx 3.1 \times 10^{-16}$ cm^2/W). The cavity length was ≈740 mm, corresponding to a repetition rate of 203 MHz. HR: high-reflection mirror; HD: high-dispersion mirrors; OC: output coupler; KM: Kerr medium (sapphire plate); H: hard aperture; R1 and R2: concave mirrors with ROC of -150 mm and -50 mm, respectively.

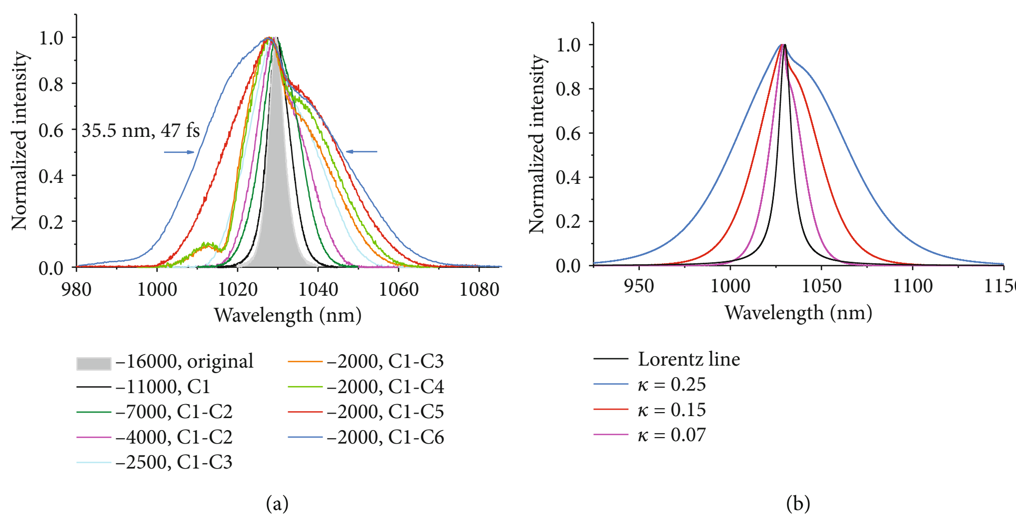

FIGURE 2: (a) Measured spectra with varied amount of Kerr plates. The spectral bandwidth gradually increased as the DKLM effect became stronger. The black line represents the original spectrum from the oscillator without any additional distributed Kerr lenses and corresponds to a pulse duration of 260 fs. The dip in the orange (C1-C3) and light green (C1-C4) curve originated from the limited bandwidth of the highly dispersive mirrors which were used in these two cases. (b) Simulated spectra. κ represents the modulation depth. The three values of κ are selected within the reasonable range, showing the increasing tendency of the modulation depth.

bandwidth limit of the Yb:YAG gain medium (Figure 2(a)). With six nonlinear plates (C1–C6) inserted, 3.5 W pulses with near-bandwidth-limited pulse duration of 47 fs were yielded. The corresponding spectrum spans from 980 nm to 1070 nm with a width of 35.5 nm at FWHM, which is four times wider than the emission bandwidth of the Yb:YAG crystal (9 nm at FWHM). These results and parameters are summarized in Table 1. As can be seen from Table 1, for any fixed output coupling ratio, the output pulse durations were shorter in the presence of more Kerr plates, confirming the importance of SAM in shortening the pulse duration. The introduced GDD listed in Table 1 was chosen to obtain the shortest pulse generation with a stable mode locking for each case, and lower GDD would not enable the mode locking or make the mode locking instable. Simulations based on the generalized complex nonlinear Ginzburg-Landau equation were also carried out (see Supplementary Materials (available here)), showing good qualitative agreement with the experimental results (Figure 2(b)).

Figures 3(a) and 3(b) show the spectrum and pulse duration of the thin-disk oscillator with the most nonlinear plates inserted, which were measured by a home-built frequency-resolved optical gating (FROG) apparatus. Due to the intrinsic coupling of self-phase modulation and self-amplitude modulation, an increase in SAM is inextricably linked to an increased SPM. The nonlinear soliton phase shifts are on the order of 4 rad. Despite such excessive nonlinear phase shift, the mode-locked pulses were very stable, exhibiting nearly flat phase over their output spectral bandwidth. The oscillator repetition frequency was characterized with an RF spectrum analyzer, showing a high signal-to-noise ratio of 81 dB at a resolution bandwidth of 100 Hz (Figure 3(d)).

Table 1: Summary of the results with a different number of nonlinear plates. Pump: pump power; d_{KM}: thickness of KM; mirror GDD: roundtrip dispersion introduced by HD mirrors; OC: output coupling rate; τ: output pulse duration; P_{avg}: average power; $P_{p\text{-}intra}$: intracavity peak power; $\eta_{O\text{-}O}$: optical-to-optical efficiency.

Inserted plates	Pump (W)	d_{KM} (mm)	Mirror GDD (fs^2)	OC	τ (fs)	P_{avg} (W)	$P_{p\text{-}intra}$ (MW)	$\eta_{O\text{-}O}$
None	312	1	-16000	10%	260	75	12.5	24%
C1	280	1	-11000	10%	194	53	11.8	19%
C1-C2	308	1	-7000	10%	145	40	12.0	13%
C1-C2	278	2	-4000	10%	118	20	7.4	7.2%
C1-C3	309	2	-2500	10%	80	17	9.2	5.5%
C1-C3	217	2	-2000	5%	71	10	12.2	4.6%
C1-C4	200	2	-2000	5%	65	8	10.7	4%
C1-C5	126	2	-2000	3%	56	4.8	12.4	3.8%
C1-C6	100	2	-2000	3%	47	3.5	10.8	3.5%

It indicates stable mode-locked operation of the oscillator and compares well with the performance of other thin-disk oscillators [26]. Furthermore, the intensity stability of the output, at 0.3% r.m.s, integrated from 1 Hz to 100 kHz, is similar to that of typical Kerr lens mode-locked oscillators. Despite the oscillator being assembled on a basic breadboard and simply surrounded by aluminum plates, it can run stably for several hours in the mode-locked regime. Considerable improvement in the oscillator's long-term stability can be expected by enclosing it in a robust temperature-controlled housing. Figure 3(e) reveals a near ideal Gaussian beam with a beam quality factor of $M^2 < 1.1$ measured for both axes.

Compared to bulk and fiber oscillators, thin-disk oscillators have proven excellent power and energy scalability [28, 35]. This scalability originates from the freedom to implement different beam sizes while maintaining the high gain and low thermal distortion. Moreover, due to the spatial separation of the Kerr medium and gain medium, the beam size in the Kerr medium can be increased while increasing the pump power applied to the disk. In this work, this kind of geometrical energy scaling was realized via an increase in the radius of curvature (ROC) of the two concave mirrors (R1 and R2) from 50 mm/150 mm (Figure 1) to 100 mm/250 mm, while keeping the output coupling and nonlinear plates (C1–C6) unchanged. The lengths of the two cavity arms were extended in proportion to the increase in ROC for each arm, lowering the repetition rate from 203 MHz to 113 MHz. Consequently, the intracavity peak power was increased from 12 MW to 25 MW. Pulses with an average power of 4.5 W and a pulse duration of 53 fs were obtained, and the corresponding optical-to-optical efficiency was 3.5%.

To prove that the additional Kerr lenses enhanced the self-focusing effect and thus influence the cavity mode, the output beam profiles for different cavity configurations were measured. Figure 4(a) shows the beam profiles measured behind the OC with a short distance when the pulse durations were 65 fs (plates C1–C4) and 118 fs (with plates C1 and C2). The beam profile corresponding to the pulse duration of 65 fs showed a significantly larger beam diameter outside the OC (which corresponds to a smaller beam diameter inside the OC due to the strong divergence of the beam) compared to that of 118 fs, indicating a change in the overall self-focusing (Kerr lensing) effect. Although the telescope position was also adjusted when additional plates were inserted, the oscillator cannot be mode-locked in the new telescope position if the additional plates were absent. This confirmed the importance of the plates' self-focusing effect in altering and stabilizing the cavity mode.

A strong spectral breathing was observed as the pulse propagates through the laser cavity, indicating a possible dissipative soliton operation. As illustrated in Figure 4(b), three spectra were measured at different positions in the cavity where 47 fs pulses were generated. The DKLM action, together with the gain filtering and dispersion compensation effects, resulted in different spectral shapes and widths at different cavity locations. The Kerr effect caused spectral broadening during the propagation through the plates. The gain medium then acted as a spectral filter. The chirp was subsequently compensated by the dispersive mirrors, with the spectral width mostly unaffected. The strongest spectral change occurred after propagation through the multiple nonlinear plates, as observed in the transmitted beam behind the R2 for the beam coming from HR end mirror (see the black curve in Figure 4(b)). The spectrum showed a dip around the wavelength of 1040 nm. This shape suggests a strong nonlinear phase shift during the propagation of the laser beam and the presence of strong self-phase modulation in the Kerr medium. The situation is analogous to dispersion-managed fiber lasers [36] but is rather exotic for bulk solid-state oscillators.

A reason for the decrease in efficiencies (Table 1) is the lower effective gain caused by the poor overlap of the spectrum with the gain emission profile. In contrast to the usual KLM regime where emission bandwidth-limited pulses are produced, significant parts of the DKLM spectrum (see Figure 3(a)) have nearly no overlap with the main emission profile of Yb:YAG gain medium, reducing the overall gain. Another reason for the reduction in optical-to-optical efficiencies and average powers (see Table 1) when more plates are inserted is the losses induced by the multiple Kerr plates. Since there are six uncoated plates in the beam path

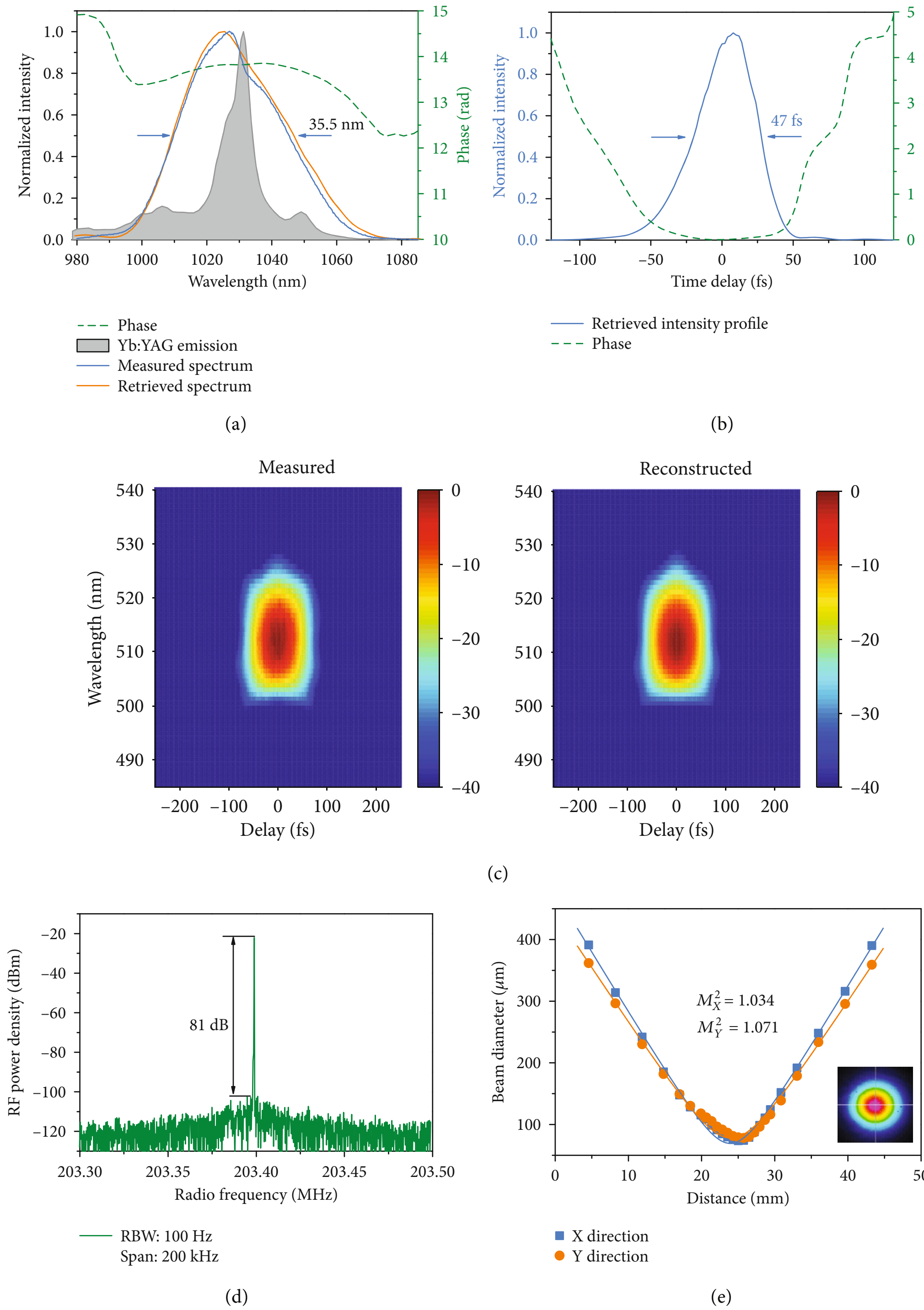

Figure 3: Characteristics of the pulses. (a) Measured and retrieved spectra of the pulses compared with the emission spectrum of Yb:YAG. The measured spectrum extends from 980 to 1070 nm (OSA, Ando AQ-6315A). (b) Retrieved temporal intensity showing a pulse duration of 47 fs. (c) The comparison of the measured and retrieved FROG traces. (d) Fundamental RF spectrum measured at a resolution bandwidth of 100 Hz showing a signal-to-noise ratio of 81 dB (Agilent, E4447A). (e) Measured beam quality ($M^2 \approx 1.1$) and the beam profile.

(excluding the KM), the losses resulting from the surface reflection cannot be ignored. As a result, the output coupling ratio had to be decreased when more Kerr plates were inserted to compensate for the increased cavity loss.

In order to increase the efficiency, multipass configuration can be implemented to increase the overall gain within a round trip [28, 37]. Those separate plates can be antireflection coated or replaced by a single plate either with larger thickness or with high nonlinear coefficient so as to decrease the reflection loss from the surfaces of the plates. Besides, the combination of the DKLM method and other gain media with more broadband emission spectrum would significantly

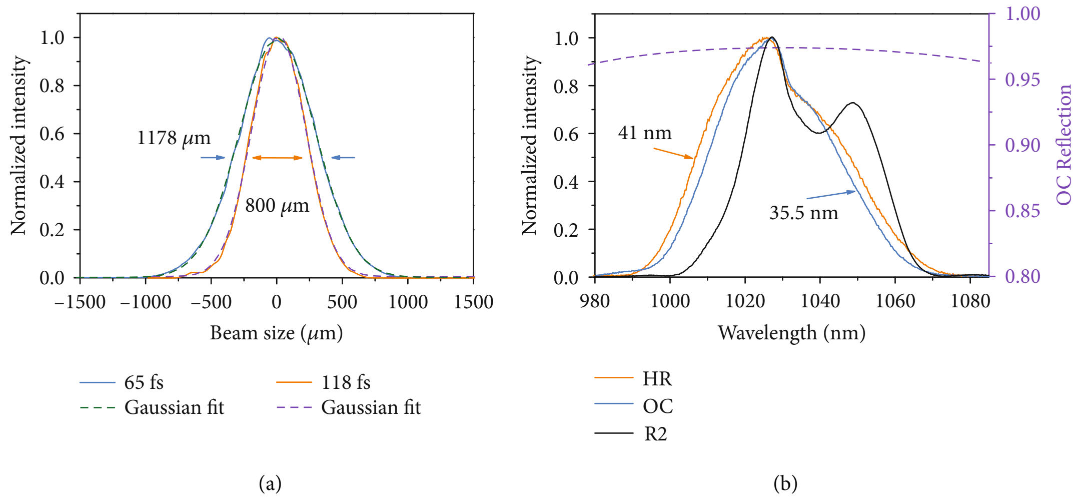

Figure 4: (a) Comparison of the output beam diameters at pulse durations of 65 fs (with plates C1-C4) and 118 fs (with plates C1 and C2), respectively. (b) Different spectral shapes and widths at different positions (behind the HR mirror, behind the OC, and behind the R2 for the beam transmitting from HR end mirror), showing the breathing behavior. The corresponding Fourier transform limit of the pulse duration is calculated to be 40 fs, 44 fs, and 37 fs, respectively. The dashed curve represents the theoretical reflectivity curve of the OC, indicating that the influence of the OC spectral characteristics on the output spectral shape is negligible.

improve efficiencies, and shorter pulses can be expected. Even with the current oscillator, a further decrease in the pulse duration would be possible by compensating for the third-order intracavity dispersion and implementing more broadband coatings for the disk.

4. Conclusion

In conclusion, we demonstrated a novel mode-locking technique named DKLM based on an Yb:YAG thin-disk oscillator. The technique increases the overall modulation depth for the passive mode locker by distributing various Kerr lenses at proper locations inside the oscillator cavity. This method enables output pulse durations well below what the emission bandwidth limit (FWHM) of the gain medium can support. The first implementation of this concept with an Yb:YAG thin-disk oscillator resulted in a wide tunability of the pulse durations. The application of this method to such broadband gain media as Cr:ZnSe or Ti:Sapphire might make these systems to deliver even more broadband spectra. Besides, pronounced soliton breathing was observed, making the DKLM oscillator a potential platform for the interesting study of dissipative soliton in bulk solid-state lasers. The oscillators based on the DKLM concept generating directly short pulses will impact diverse applications such as multiphoton microscopy [38, 39] and broadband infrared generation [40].

Data Availability

The data that support the plots within this paper and other findings of this study are available from the corresponding authors upon reasonable request.

Additional Points

Code Availability. The codes that support the simulation within this paper and other findings of this study are available from the corresponding authors upon reasonable request.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

Authors' Contributions

The main setup was designed and built by JZ, JB, and OP. The measurements were taken by JZ, MP, JB, and MS. The customized thin-disk modules were prepared by DB and DS. The specialized dielectric optics were designed and fabricated by VP. The data was analyzed and interpreted by JZ, QW, JB, MS, AA, KM, and OP. The simulation was carried out by VK. The experiment was conceived by ZW, FK, and OP. The project was coordinated by OP. All authors reviewed and contributed to the final manuscript.

Acknowledgments

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Supplementary Materials

Supplementary Figure 1: dependency of the asymptotical FWHM width T on the net modulation depth coefficient $\kappa = \sum_m \kappa_m$ for different net loss coefficients. Supplementary Figure 2: numerical spectral profiles for different modulation depths κ. Supplementary Figure 3: pulse width T vs. modulation depth along the stability border at different values of the saturation parameter ζ. Supplementary Figure 4: anomalous GDD corresponding to curves in Supplementary Figure 3. Supplementary Figure 5: low-loss regime. Supplementary Figure 6: cavity mode of the continuous-wave thin-disk oscillator. *(Supplementary Materials)*

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