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RESEARCH ARTICLE

Thin-disk multi-pass amplifier for kilowatt-class ultrafast lasers

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Abstract
We report on an improved ytterbium-doped yttrium aluminum garnet thin-disk multi-pass amplifier for kilowatt-level ultrafast lasers, showcasing excellent beam quality. At a repetition rate of 800 kHz, the 6.8 ps, 276 W seed laser is amplified up to an average power of 1075 W, corresponding to a pulse energy of 1.34 mJ. The 36-pass amplifier is designed as a compact mirror array in which the beam alternately propagates between the mirrors and the disk by a quasi-collimated state. We adopted a quasi-collimated propagation to confine stray and diffracted light by the slight curvature of the disk, which enables us to achieve an outstanding extraction efficiency of up to 57% with excellent beam quality in stable laser operation at high power. The beam quality at 1075 W was measured to be $M^2 < 1.51$. Furthermore, stability testing was demonstrated with a root-mean-square power fluctuation of less than 1.67% for 10 min.

Keywords: high-power laser; kilowatt level; multi-pass amplifier; thin-disk laser; ultrafast laser

1. Introduction

Ultrafast laser systems combining high-intensity pulses with an average power exceeding kilowatt (kW)-level output power represent a significant advancement in laser technology. The realization of kW-level ultrafast laser systems at a high repetition rate opens up new avenues in various fields, such as the pumping of optical parametric amplifiers[1,2], particle acceleration[3,4] and X-ray generation[5,6]. Parallelly, in many applications such as micromachining and material processing, high-power ultrafast lasers at a high repetition rate allow for high-precision, high-throughput manufacturing processes, including cutting, drilling and surface structuring of hard material[7–9] and glass processing[10,11] with minimal thermal damage. For efficient laser operations at a high processing speed providing high surface quality, laser sources with high-energy pulses simultaneously with a high pulse repetition rate, diffraction-limited beam quality and average power are crucial to boost production at an industrial scale.

In recent years, various concepts, including fiber amplifiers[12,13], slab amplifiers[14,15] and thin-disk amplifiers[16,17], have been proven effective technologies for delivering high-power lasers at high repetition rates. However, scaling to kW-level average power efficiently with mJ-level pulse energy while preserving ultrafast pulse durations at high beam quality presents a formidable challenge, primarily due to the rise of nonlinearities and the increased demand for efficient heat dissipation. Techniques such as coherent beam combining (CBC) and chirped pulse amplification (CPA)[18,19] are generally utilized in such amplifiers to scale lasers to the kW level,

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keeping the nonlinear effects under control and avoiding damage to optical components. However, large group delay dispersion and pulse stretching and recompression optics are required to realize CPA, making the system very complex and expensive.

Among the plethora of technologies, the CPA-free thin-disk regenerative amplifier stands out as a remarkable solution, offering a unique combination of high output power and excellent beam quality. The efficient one-dimensional heat dissipation of thin-disk design reduces thermal issues such as lensing and birefringence, enhancing beam quality, and thus can support high pump intensities up to 10 kW/cm^2. On the other hand, the large beam diameter in the active medium maintains low intensities, preventing nonlinear effects and enabling kW-class output powers with pulse energies in the millijoule range. Ueffing *et al.*[20] demonstrated a 207 W CPA-free thin-disk regenerative amplifier at 100 kHz repetition rate exhibiting the optical conversion efficiency of less than 31%. Recently, a CPA-free thin-disk regenerative amplifier with an average output power of 154 W at 1 MHz pulse repetition with the highest efficiency of 61% was realized[21]. The further increase in average output power and pulse energy of thin-disk regenerative amplifiers becomes challenging due to the emergence of nonlinearities and the limited accessibility of Pockels cells with large apertures. A thin-disk multi-pass system design[22] is a key technology in addressing the critical challenges associated with scaling ultrafast laser systems to higher powers and offers large flexibility regarding repetition rate adaptation in which regenerative amplifiers show limitations. In this concept, increasing the number of beam passes on thin disks through geometrical folding increases power to the kW level without CPA. A powerful seed source is generally required to saturate the gain effectively owing to limited gain per pass. A two-stage thin-disk multi-pass amplifier (TDMPA) was realized with an output power of 1.9 kW at 1.3 ps pulses, exhibiting the final stage optical conversion efficiency of 60% and the beam quality of 2.3[23]. The average output power of 1.4 kW and pulse energy of 4.7 mJ at 8 ps were achieved by a TDMPA seeded by a regenerative amplifier with an average power of 115 W. The amplifier exhibits an optical conversion efficiency of 48% and $M^2 > 1.4$[24]. Recently, a 7.7 ps, two-stage TDMPA delivered a maximum output power of 2.05 kW at a pulse repetition of 300 kHz with a pulse energy of 6.8 mJ, exhibiting the conversion efficiency of 50% and the beam quality of 1.5[25].

Since a crucial aspect of TDMPAs involves amplifying laser radiation to power levels exceeding several hundred watts, or even higher, the utilization of high-power pump sources becomes indispensable. However, these high pumping intensities invariably result in elevated temperatures within the gain medium and surrounding gas[26,27]. The formation of thermal lensing follows predictable patterns and can be compensated by efficient cooling and propagation optimizing. In addition, challenges arise from the formation of gas wedges and gas lenses due to the uneven and asymmetric heating of the air. These challenges present significant obstacles, especially in long-distance propagation of the beam required for TDMPAs, leading to considerable air perturbation. To mitigate the impact of the air wedge on the propagating laser beam, one approach involves implementing a retro-reflecting mirror pair (RMP)[28]. Simultaneously, thermally induced mechanical deformation also contributes to insufficient stability, resulting in gradual drifts. These issues cause the seeded beams to walk off from the pumped position on the disk, reducing extraction efficiency and inducing beam diffraction.

Furthermore, optical elements are susceptible to surface deformation due to the intrinsic stress and clamping stress from mechanical components, resulting in wavefront distortion and degrading the beam quality of the propagating beam. Consequently, these distortions become temperature-dependent, varying with laser power and the thermalization time of the mounting mechanics[29].

To overcome these challenges and enhance the efficiency of the TDMPA, we implemented improvements to crucial components while preserving the core concept of the TDMPA unchanged. In this paper, we demonstrate an ultrafast multi-pass thin-disk laser amplifier generating an average output power of 1.075 kW, in a near-diffraction-limited beam quality M^2 of less than 1.51 with an extraction efficiency of 57%. Operating at a repetition rate of 800 kHz, the pulses with a duration of 6.26 ps deliver an energy of 1.34 mJ without the need for CPA. The desktop-level laser system with a size of 1 m $\times$ 0.3 m $\times$ 0.3 m exhibited stable operation for over 10 min at room temperature, which paves the way for significant progress in many applications, especially for material processing.

2. Experimental setup

A schematic of the experimental setup is shown in Figure 1. The system consists of a seed laser and a multi-pass amplifier. The seed laser, based on thin-disk amplifier, delivers 276 W of average output power at 1030 nm with a pulse repetition rate of 800 kHz at 6.8 ps pulse duration, resulting in single-pulse energy of 345 μJ. The beam quality factor of the output beam with a diameter of 3.0 mm was measured to be $M^2 = 1.3$.

Subsequently, the seed laser was injected to the TDMPA to scale the power to a higher level. The setup comprises a multi-pass cell utilizing a homemade ytterbium-doped yttrium aluminum garnet (Yb:YAG) thin-disk laser head. The TDMPA operates with 36 individually adjustable mirrors arranged in an array on a water-cooled block. This configuration allowed for folding the seed beam 18 times over the disk, resulting in an average power of approximately 1 kW. A custom-engineered 48-pass thin-disk pump module

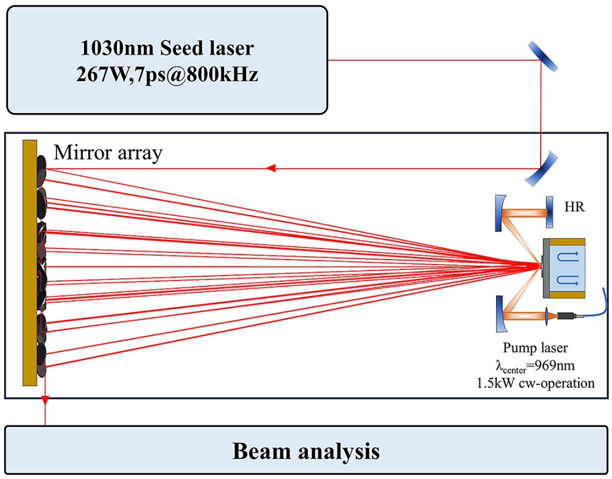

Figure 1. Experimental setup of the amplifier system.

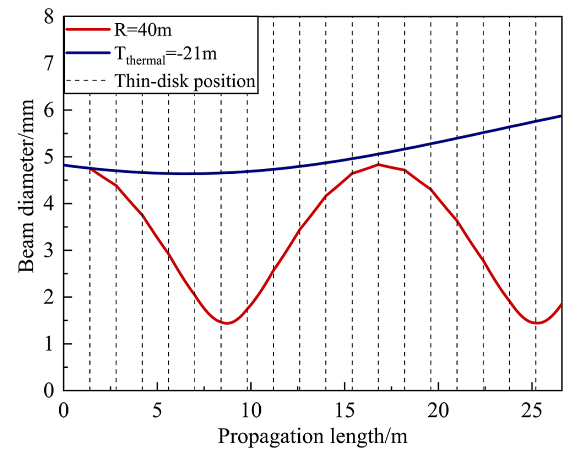

Figure 2. Evolution of the beam diameter during propagation within the TDMPA.

was employed in conjunction with a plane-parallel Yb:YAG thin-disk crystal for the TDMPA, resulting in an absorption efficiency surpassing 95%[30]. The disk had a diameter of 20 mm and a concave radius of curvature (ROC) of 40 m. The thickness of the disk was chosen to be 100 μm at a doping concentration of 9%. Anti-reflection coatings of 1030 and 969 nm were applied to the front face of the disk, while high-reflection coatings were applied to the rear face. The Yb:YAG thin disk was bonded to a 3 mm-thick diamond substrate. An efficient impingement cooling structure using a porous copper nozzle with a temperature of 20°C was employed on the back side of the diamond to effectively remove the residual heat from the thin disk. The TDMPA was pumped by a 1500 W top-hat laser diode with a diameter of 6 mm at a stabilized wavelength of 969 nm (‘zero-phonon-line pumping’).

The disk was placed at a distance of 700 mm in front of the mirror array, resulting in the overall propagation length in the TDMPA of 25.2 m. In order to maintain the beam collimation and beam quality, the diameter was scaled to 4.8 mm before the TDMPA with a telescope, which corresponds to approximately 80% of the pump diameter on the disk. With the mode-matching design, high-order modes were eliminated, and thus the beam quality was improved as much as possible. During propagation through the amplifier, the beam diameter fluctuated between 1.5 and 4.8 mm, as detected by a coaxial camera.

3. Results and discussion

The laser system is designed to guide the seed beam through approximately 25.2 m in the multi-pass amplifier. Due to the fixed beam parameter product of Gaussian beams, a larger beam spot resulted in less divergence during propagation. With all folding mirrors being plane mirrors and the disk crystal having a large ROC, the amplified beam remained almost collimated throughout the propagation length. Calculations based on the propagation matrix revealed the beam diameter varies from 1.5 to 4.8 mm in the TDMPA, as shown by the red curve in Figure 2. Assuming a strong convex thermal lens of $F_{\text{thermal}} = -21$ m at 8 kW/cm^2 intensity[31], the ROC of the disk would increase but still be concave. The thermal lens mitigated the fluctuations, leading the entire optical path closer to a collimated beam. Consequently, the beam diameter was between 4.8 and 5.8 mm in the TDMPA without noticeable tight focus in air, as indicated by the blue curve in Figure 2. For this multi-pass configuration, we adopted the quasi-collimated (QC) multi-pass design. Compared to conventional 4f-propagation schemes and resonator-based optical Fourier transform propagation schemes, the QC propagation approach periodically focuses the amplified beam via the small curvature of the disk, reducing the beam divergence from diffraction. Such multi-pass beam propagation schemes are easier to set up, offering flexibility in beam control and stability. They also maintain a larger

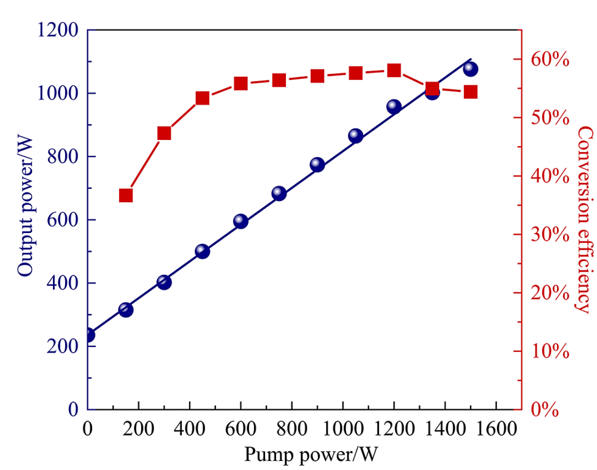

Figure 3. Average output power and extraction efficiency of the TDMPA as a function of the pump power.

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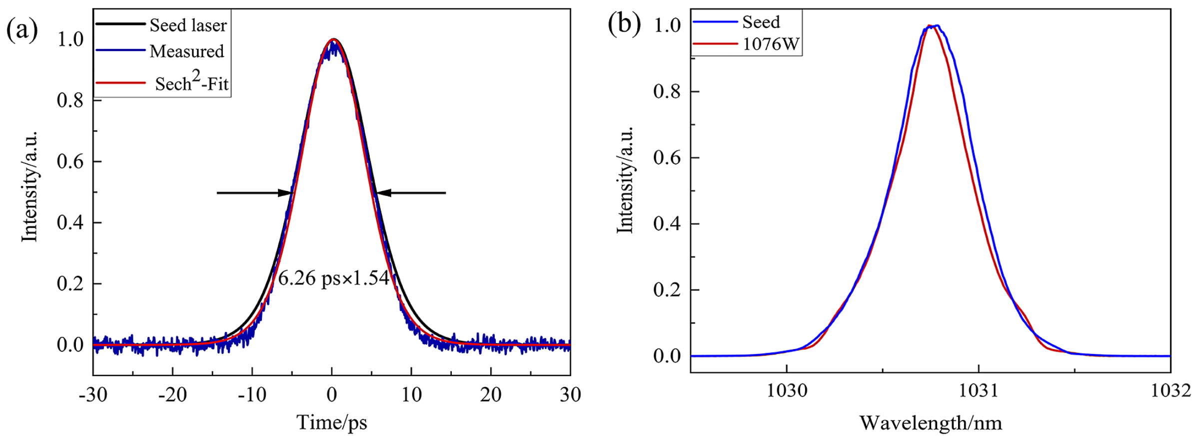

Figure 4. (a) Pulse widths and (b) optical spectra of the pulses at the maximum output power for the seed laser and TDMPA.

beam size along the propagation length, making the system less sensitive to phase front distortions and allowing for high power at good spatial and temporal beam quality[32,33]. With a larger beam size, air ionization at high peak powers is effectively prevented; thus the requirement for a vacuum environment is eliminated. In our experimental setup, there was no pursuit of excessive matching between the wavefront curvature and the disk curvature, thus eliminating the stringent requirements for propagation distances between the disk and reflectors. However, the beam diameter fluctuations during the amplification phase were minimized as much as possible. Stable amplification for high-power lasers was achieved without uncertainties, such as nonlinear effects and air ionization.

The average output power of the TDMPA and the calculated extraction efficiency are depicted in Figure 3 as a function of the pump power. The extraction efficiency is calculated by the relationship as follows[29]:

$$\eta = \frac{P_{\text{ext}}}{P_{\text{Pump}}} = \frac{P_{\text{out}} - P_{\text{seed}}}{P_{\text{Pump}}}, \tag{1}$$

where P_{pump} is the pump power; P_{ext} is the extraction power from the TDMPA given by $P_{\text{out}} - P_{\text{seed}}$ with P_{out} being the amplified power and P_{seed} the seed power before injecting to the TDMPA. After injecting to the TDMPA, the 276 W seed laser decreased to 236 W without pump power due to the disk absorption and 36 reflectors. The output power increased linearly throughout the entire process of enhancing pump power. With a pump power of 1500 W, we achieved the maximum output power of 1075 W, corresponding to an extraction efficiency of 54% and a gain of 3.9. The gain of the multi-pass amplifier exhibited a saturation trend when the pump power exceeded 1200 W, corresponding to a maximum extraction efficiency of 57%. Considering a repetition frequency of 800 kHz, the output pulse energy reached 1.34 mJ. The efficiency roll-over occurred because the seed power was insufficient to efficiently extract the stored energy at high pump powers.

The pulse widths of the seed laser and the 1075 W laser from the TDMPA were measured by an auto-correlator (Pulse Check, APE), as shown in Figure 4(a). Assuming a sech^2 fitting, the pulse width of the seed laser was 6.82 ps. At the highest output power of 1075 W, the pulse width from the TDMPA exhibited a slight narrowing with 6.26 ps. Sufficient pulse fidelity was confirmed from the multi-pass amplifier even though the pulses had been amplified to the millijoule level. Compared to rod and fiber gain media, there were no significant changes in the pulse width, indicating that the system dispersion and nonlinearity have no noticeable effects on the pulse temporal characteristics.

The difference in the output spectrum of the seed pulses and the amplified pulses at maximum output power was measured by an optical spectrum analyzer (Yokogawa, AQ6376), as shown in Figure 4(b). The full width at half maximum (FWHM) values of the spectrum from the pulses were measured to be 0.49 and 0.45 nm, respectively, with both centered at 1030.8 nm. No significant modulations in the spectrum were observed with increasing power and energy.

The beam quality of the laser at 1075 W was measured with a beam quality analyzer (Beamsquare, SP90440, Ophir), as shown in Figure 5(a). The inset illustrates the far-field intensity profile, exhibiting a well-defined Gaussian profile for the laser. The M^2 values are measured to be 1.59 for the x-axis and 1.43 for the y-axis, yielding an average M^2 value of 1.51. The measurement results indicate a degradation in the beam quality after the TDMPA. The degradation of beam quality primarily arose from the thermal lensing and the nonlinear effects of the optical components. These nonlinear adverse effects induced wavefront distortion within the TDMPA, contributing to the asymmetry observed in the output laser. However, for high-power lasers exceeding 1 kW, single-mode operation with an M^2 of 1.51 is adequate and significant. The stability curve of the amplifier system operating at 1.054 kW for 10 min is shown in Figure 5(b). A normalized root-mean-square (RMS) deviation of 1.67% was obtained at an average output power of 1018 W. The near-

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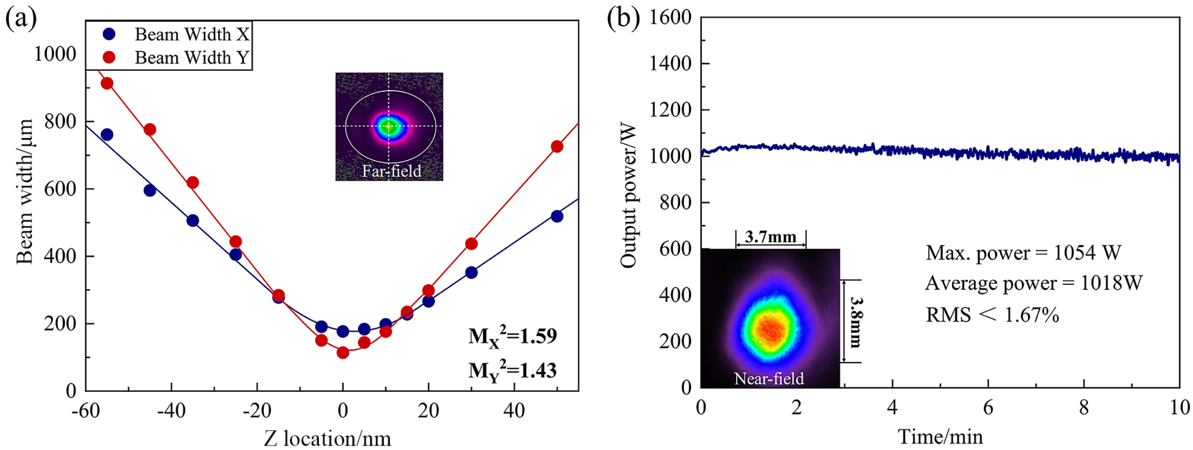

Figure 5. (a) Beam quality measurement at 1.075 kW of average output power. (b) Power stability at 1.054 kW.

field intensity profile also exhibited a Gaussian profile for the output laser, as shown by the inset of Figure 5(b). Aberrations were observed in the near-field intensity profile, probably caused by the thermal effects of the optical components. Compared to the simulated results in Figure 2, the output laser with a diameter of 4.3 mm was slightly smaller, possibly due to the excessive thermal lens assumption for the TDMPA.

4. Conclusion

In summary, an average output power of 1075 W at 800 kHz was achieved by a CPA-free Yb:YAG TDMPA system, accompanied by an excellent extraction efficiency of 57%. The 6.26-ps pulses at the maximum average power exhibit excellent temporal and spatial characteristics due to the unique geometric structure of the thin-disk crystals. The kW ultrafast laser operates in single mode, with an M^2 factor of 1.51. Stable operation for over 10 min at room temperature was also observed with an RMS of less than 1.67%. This work highlights the significant potential of thin-disk laser technology in delivering high-power picosecond laser outputs for various scientific and industrial applications.

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References

1. 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).
2. Y. Zobus, C. Brabetz, J. Hornung, J. B. Ohland, D. Reemts, J. P. Zou, M. Loeser, D. Albach, U. Schramm, and V. Bagnoud, High Power Laser Sci. Eng. **11**, e48 (2023).
3. A. J. Goers, G. A. Hine, L. Feder, B. Miao, F. Salehi, J. K. Wahlstrand, and H. M. Milchberg, Phys. Rev. Lett. **115**, 194802 (2015).
4. X. M. Wang, R. Zgadzaj, N. Fazel, Z. Y. Li, S. A. Yi, X. Zhang, W. Henderson, Y. Y. Chang, R. Korzekwa, H. E. Tsai, C. H. Pai, H. Quevedo, G. Dyer, E. Gaul, M. Martinez, A. C. Bernstein, T. Borger, M. Spinks, M. Donovan, V. Khudik, G. Shvets, T. Ditmire, and M. C. Downer, Nat. Commun. **4**, 1988 (2013).
5. B. A. Reagan, C. Baumgarten, E. Jankowska, H. Chi, H. Bravo, K. Dehne, M. Pedicone, L. Yin, H. C. Wang, C. S. Menoni, and J. J. Rocca, High Power Laser Sci. Eng. **6**, e11 (2018).
6. M. A. Purvis, V. N. Shlyaptsev, R. Hollinger, C. Bargsten, A. Pukhov, A. Prieto, Y. Wang, B. M. Luther, L. Yin, S. J. Wang, and J. J. Rocca, Nat. Photonics **7**, 796 (2013).
7. M. Malinauskas, A. Zukauskas, S. Hasegawa, Y. Hayasaki, V. Mizeikis, R. Buividas, and S. Juodkazis, Light Sci. Appl. **5**, 14 (2016).
8. E. H. Penilla, L. F. Devia-Cruz, A. T. Wieg, P. Martinez-Torres, N. Cuando-Espitia, P. Sellappan, Y. Kodera, G. Aguilar, and J. E. Garay, Science **365**, 803 (2019).
9. C. Liang, Z. Li, C. Wang, K. Li, Y. Xiang, and X. S. Jia, Opt. Laser Technol. **167**, 109828 (2023).
10. K. Cvecek, S. Dehmel, I. Miyamoto, and M. Schmidt, Int. J. Extreme Manuf. **1**, 042001 (2019).
11. H. G. Liu, W. X. Lin, and M. H. Hong, Light Sci. Appl. **10**, 23 (2021).
12. J. X. Zuo, H. J. Yu, S. Z. Zou, Z. Y. Dong, C. J. He, S. Xu, C. Y. Ning, X. C. Chen, X. Y. Li, and X. C. Lin, High Power Laser Sci. Eng. **11**, e22 (2023).

https://doi.org/10.1017/hpl.2024.48 Published online by Cambridge University Press

13. H. Stark, J. Buldt, M. Müller, A. Klenke, and J. Limpert, Opt. Lett. **46**, 969 (2021).
14. C. Ma, Z. Liu, K. Liu, Y. Yu, X. J. Wang, Y. Bo, D. F. Cui, and Q. J. Peng, Opt. Laser Technol. **148**, 107767 (2022).
15. Y. Chen, K. Liu, J. Yang, F. Yang, H. W. Gao, N. Zong, L. Yuan, Y. Y. Lin, Z. Liu, Q. J. Peng, Y. Bo, D. F. Cui, and Z. Y. Xu, J. Opt. **18**, 075503 (2016).
16. W. Schneider, A. Ryabov, C. Lombosi, T. Metzger, Z. Major, J. A. Fülöp, and P. Baum, Opt. Lett. **39**, 6604 (2014).
17. F. Saltarelli, I. J. Graumann, L. Lang, D. Bauer, C. R. Phillips, and U. Keller, Opt. Express **27**, 31465 (2019).
18. J. X. Zuo and X. C. Lin, Laser Photonics Rev. **16**, 2100741 (2022).
19. M. Müller, C. Aleshire, A. Klenke, E. Haddad, F. Légaré, A. Tünnermann, and J. Limpert, Opt. Lett. **45**, 3083 (2020).
20. M. Ueffing, R. Lange, T. Pleyer, V. Pervak, T. Metzger, D. Sutter, Z. Major, T. Nubbemeyer, and F. Krausz, Opt. Lett. **41**, 3840 (2016).
21. S. Z. Xu, Y. B. Gao, X. Liu, Y. W. Chen, D. Q. Ouyang, J. Q. Zhao, M. Q. Liu, X. Wu, C. Y. Guo, C. T. Zhou, Q. T. Lue, and S. C. Ruan, High Power Laser Sci. Eng. **12**, e14 (2023).
22. H. L. Wang, J. Dong, H. Y. Liu, J. J. Hao, X. Zhu, and J. W. Zhang, Acta Photonica Sin. **50**, 19 (2021).
23. T. Dietz, M. Jenne, D. Bauer, M. Scharun, D. Sutter, and A. Killi, Opt. Express **28**, 11415 (2020).
24. J. P. Negel, A. Loescher, A. Voss, D. Bauer, D. Sutter, A. Killi, M. A. Ahmed, and T. Graf, Opt. Express **23**, 21064 (2015).
25. C. Röcker, A. Loescher, F. Bienert, P. Villeval, D. Lupinski, D. Bauer, A. Killi, T. Graf, and M. A. Ahmed, Opt. Lett. **45**, 5522 (2020).
26. X. Y. Ma, L. Li, G. Z. Zhu, and X. Zhu, Opt. Laser Technol. **164**, 109482 (2023).
27. A. Diebold, F. Saltarelli, I. J. Graumann, C. J. Saraceno, C. R. Phillips, and U. Keller, Opt. Express **26**, 12648 (2018).
28. J. P. Negel, A. Voss, M. A. Ahmed, D. Bauer, D. Sutter, A. Killi, and T. Graf, Opt. Lett. **38**, 5442 (2013).
29. A. Loescher, F. Bienert, C. Röcker, T. Graf, M. Gorjan, J. A. D. Au, and M. A. Ahmed, Opt. Continuum **1**, 747 (2022).
30. Y. Gao, S. Xu, Y. Chen, M. Liu, D. Ouyang, X. Wu, J. Chen, J. Zhao, C. Guo, X. Liu, Q. Lv, and S. Ruan, Acta Photonica Sin. **53**, 2 (2024).
31. M. A. Ahmed, C. Roecker, A. Loescher, F. Bienert, D. Holder, R. Weber, V. Onuseit, and T. Graf, Adv. Opt. Technol. **10**, 285 (2021).
32. M. Zeyen, L. Affolter, M. A. Ahmed, T. Graf, O. Kara, K. Kirch, M. Marszalek, F. Nez, A. Ouf, R. Pohl, I. Schulthess, S. Rajamohanan, P. Yzombard, K. Schuhmann, and A. Antognini, Opt. Express **32**, 1218 (2024).
33. M. Zwilich and B. Ewers, OSA Continuum **3**, 3176 (2020).