Infrared Physics & Technology 134 (2023) 104855

Contents lists available at ScienceDirect

Infrared Physics and Technology

journal homepage: www.elsevier.com/locate/infrared

Near-diffraction-limited 201 W high-repetition-rate Yb:YAG regenerative thin-disk amplifier

Zhihuan Yao [a,d], Fei Chen [a,*], Yi Chen [a,*], Junjie Sun [a,d,*], Jinghua Yu [a,d], Yiwen Zhang [a], Deyang Yu [a], Yang He [a], Kuo Zhang [a], Hang Zhou [b], Ke Yang [b], Ze Zhang [c], Qin Wen [c]

[a] State Key Laboratory of Laser Interaction with Matter, Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun 130033, Jilin, China
[b] Laboratory of Electromagnetic Space Cognition and Intelligent Control Technology, Beijing 100191, China
[c] Aerospace Information Research Institute, Chinese Academy of Sciences, Beijing 100094, China
[d] University of Chinese Academy of Science, Beijing 100049, China

ARTICLE INFO

Keywords:
Ultra-fast laser
Thin disk laser
Yb:YAG
Regeneration amplifier
Chirped pulse amplification

ABSTRACT

To achieve stable and efficient amplification of seed laser, we report on a regenerative amplifier based on chirped pulse amplification and thin-disk technology, providing an average output power of 201.4 W at a repetition rate of 50 kHz before being compressed. A closed-loop control system is used to overcome the negative effects of air convection and thermal effects. The regenerative amplifier has a pulse duration of 1.28 ns, pulse amplitude stability of RMS = 2.78 %, spectrum bandwidth of 2.5 nm, and center wavelength of 1031.7 nm. The pulse duration can be theoretically compressed to 591 fs. The output power fluctuation of RMS = 0.51 % is delivered in an excellent output beam characterized by ${M_x}^2 = 1.08$ and ${M_y}^2 = 1.01$, and the optical-to-optical efficiency is 20.9 %. According to the experiment results, the regenerative amplifier proposed in this study is a perfect pre-amplification unit for amplifiers used in the chirped pulse amplification approach because it can steadily produce a chirped laser output with high average power.

1. Introduction

Since the invention of the first ruby laser in history [1], laser technology has progressed toward the production of ultra-fast lasers with high power and high energy. The laser pulse duration has continuously advanced from nanosecond (ns) to attosecond (as) level with the development of technologies like Q-switching [2] and mode-locking [3], together with the discovery and application of higher harmonic phenomena [4]. In 1985, the chirped-pulse-amplification (CPA) technology [5] was put forward as a solution to the problem of the component damage threshold limiting the further increase of the peak laser output power. In 1993, Giesen et al. at the University of Stuttgart in Germany invented the thin-disk-laser (TDL) technology [6], which effectively deals with the problem of thermal effects in the solid gain medium by using a thin-disk geometry as the gain medium. Laser output at kilowatts of average power and joules of pulse energy has been made achievable by regenerative and multipass amplifiers using thin-disk (TD) technology [7,8] for the advancement of frontier disciplines like the study of microscopic particle movement [9], strong physical fields [10], and laser electron acceleration [11]. Ultrafast and ultra-intense lasers have now become indispensable tools. It also plays a vital role in national defense and security [12] and national livelihood [13]. The pre-amplification unit of the amplifier in the CPA system has been designed in this paper as a regenerative amplifier based on thin-disk technology. It can effectively amplify the nanosecond seed pulses output from the oscillator.

Thin-disk technology was quickly used in regenerative amplifier systems due to its innovation and high-energy/high-average-power performance. C. Hominger et al. reported the thin-disk regenerative amplifier for the first time in 1997, in which a thin Yb:YAG crystal was used as the end mirror, generating pulse energies of 180 μJ at repetition rates of up to 750 Hz and 120 μJ pulses were obtained at 1 kHz, the amplified pulse duration was 2.3 ps, resulting in a pulse peak power of 78 MW [14]. In 2001, Daniel Müller et al. obtained pulse energies of 4.5 mJ at repetition rates of 1 kHz and 1 mJ at repetition rates of 10 kHz, based on the designed Yb:YAG thin-disk regenerative amplifier [15]. In

---

* Corresponding authors at: State Key Laboratory of Laser Interaction with Matter, Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun 130033, Jilin, China (J.S.).

E-mail addresses: yzhlndxwlxy@163.com (Z. Yao), feichenny@126.com (F. Chen), chenyihit@163.com (Y. Chen), 15143115236@163.com (J. Sun).

https://doi.org/10.1016/j.infrared.2023.104855
Received 19 June 2023; Received in revised form 4 August 2023; Accepted 7 August 2023

2007, Christian Stolzenburg and Adolf Giesen demonstrated a picosecond Yb:YAG thin-disk regenerative amplifier without a stretcher and compressor stage using Yb:YAG thin-disk crystal as a reflector in the regenerative amplifier, and the system achieved pulse energies of 2 mJ at repetition rates of 10 kHz and an average output power of 62 W with repetition rates up to 200 kHz [16]. In 2013, Catherine Yuriko Teisset et al. reported a thin-disk regenerative amplifier with pulse energies output higher than 50 mJ at repetition rates of 2 kHz, 40 mJ at 3 kHz, and 30 mJ at 5 kHz with pulse durations of 1.7 ps [17]. R. Fleischhaker et al. reported a sub-picosecond Yb:YAG thin-disk regenerative amplifier with a beam quality of $M^2 < 1.2$ and an average compressed output power of 160 W at repetition rates of 800 kHz as well as 85 W at 100 kHz in the same year [18]. In 2015, Sandro Klingebiel et al. reported a thin-disk regenerative amplifier containing a single thin-disk gain medium delivering 220 mJ of pulse energy at a 1 kHz repetition rate with a pulse duration of 1.9 ps [19]. In 2016, Jakub Novak et al. presented a frequency-doubled picosecond Yb:YAG thin-disk regenerative amplifier with a compressed output pulsed duration of 1.2 ps and pulse energy of 90 mJ at a repetition rate of 1 kHz, with energy stability of RMS < 0.8 % and beam quality of $M^2 < 1.2$ [20]. Robert Jung et al. upgraded and optimized the thin-disk regenerative amplifier in the same year using a motorized adjustable end mirror for remotely controlled alignment with an output pulse energy of more than 300 mJ at a repetition rate of 100 Hz with energy stability of RMS = 0.25 % and $M^2 = 1.04$ [21]. Thomas Nubbemeyer et al. reported in 2017 that a regenerative amplifier using two thin Yb:YAG disks and a ring-type cavity, providing output pulse energies of 200 mJ at a repetition rate of 5 kHz, and the average output power of more than 1 kW is delivered in an excellent output beam quality of $M^2 = 1.1$ with compressed pulse duration of 1.1 ps [22]. Peter Krotz and colleagues reported a circular regenerative amplifier based on a double thin-disk module in 2019 [23]. Before pulse compression, the output power was 1.9 kW at a repetition rate of 20 kHz, while the pump power was up to 5 kW. This regenerative amplifier's output pulse energies were 200 mJ at 5 kHz, 160 mJ at 10 kHz, and 95 mJ at 20 kHz. Also reported in the same year was a single thin-disk module regenerative amplifier used as a preamplifier in a CPA system with an output laser pulse of 230 mJ at a 1 kHz repetition rate [24]. In 2021, Dong Jing et al. at Huazhong University of Science and Technology achieved a pulsed laser output with an average power of 44.2 W, a pulse duration of 9.3 ps, and pulse energies of 220 μJ based on one thin-disk module regenerative amplifier [25]. The team achieved a laser output of 126 W at a repetition rate of 200 kHz and pulse energies of 0.96 mJ at 100 kHz based on the regenerative amplifier that two thin-disk modules connected in series simultaneously. In 2022, Jie Guo et al. at the Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences reported a nonlinear pulse compression stage device containing a Yb:YAG thin-disk regenerative amplifier and a periodically layered Kerr medium, which output a laser pulse with 195 fs pulse duration, 54 W average power, and a beam quality close to the diffraction limit at a repetition rate of 200 kHz [26].

Thin-disk regeneration amplifiers have been achieving exciting results since they were reported. In this paper, we report on recent developments of a Yb:YAG single thin-disk regenerative amplifier in which a thin crystal is synchronized as a reflector in the resonant cavity. The ability of the regenerative amplifier to produce a stable laser output is attributed to the use of a closed-loop control system that actively corrects a slightly detuned resonant cavity back to a stable operating state. The highly reflective (HR) end-mirror position is adjusted by a motorized mirror holder that can be remotely controlled outside the cavity, creating a stable closed-loop system that compensates in real time for the negative effects that lead to cavity detuning. This negative effect is mainly caused by air convection and thermal effects [27]. In the simulation design, a folded long cavity with two spherical mirrors is designed by considering the damage to the cavity components caused by the spot size at different positions. In contrast, the number of seed laser round trips in the cavity is adjusted for experimental comparison to provide a reasonable round trip time for the seed laser. The amplified laser achieved a stable output with an average power of 201.4 W at a repetition rate of 50 kHz before compression. In addition, the amplifier shows excellent power stability with 0.51 % (RMS) fluctuation and an excellent beam quality of ${M_x}^2 = 1.08$ and ${M_y}^2 = 1.01$. The optical-to-optical efficiency is better than 20 % with the pulse amplitude stability RMS of 2.78 % and the pulse duration of 1.28 ns before being compressed. The amplified laser has a spectral bandwidth of 2.20 nm at 1031.7 nm and a theoretically possible minimum pulse duration of 591 fs.

2. Setup of the regenerative amplifier

The optical setup of the Yb:YAG thin-disk regenerative amplifier can be seen in Fig. 1. It comprises a seed laser, a 48-pass pump source, an ns-level seed source, a Pockels cell (PC), a single thin-disk module regenerative amplifier cavity, an optical isolator, a Faraday rotator, and a thin film polarizer (TFP). The seed laser is delivered by a commercial fiber master oscillator power amplifier emitting pulse energy of 10 μJ with a pulse bandwidth of 1.2 ns at repetition rates of 50 kHz after selecting the rate, and a double-lens combination (M14, M15) is used to collimate the seed laser for beam expansion. The seed laser is coupled into the amplifier for single round-trip transmission through the polarize and quarter-wave plate. The seed laser can be locked within the amplifier by adjusting the electrical pulse delay of the PC, and its round-trip time in the cavity depends on the electrical pulse width of the PC. Using a Faraday rotator with polarization to separate the seed laser and the output laser.

The used pump module is shown in Fig. 2 with a folded 4f structure, and the pump light is reflected 24 times by the Yb:YAG crystal. The pump spot on the gain medium has a diameter of 6.6 mm. The pump diode delivers up to 1.4 kW peak power at 969 nm wavelength from a fiber. This wavelength matches the zero-phonon line transition of the gain material and reduces the heat generation on the disks due to the reduced quantum defect. The single Yb:YAG (7 %) thin-disk modules is equipped with disks of a thickness of 215 μm and 12 mm diameter and the front and back surfaces of the Yb:YAG thin-disk crystal are covered with transmissive and highly reflective coatings for the pump and seed lasers, respectively. The Yb:YAG thin-disk crystal functions as an amplifier cavity mirror while providing the required gain for amplification of the seed laser and its equivalent radius of curvature −58 m at the pump power of 962.4 W. The diamond is used as the backward heat sink of the gain medium, while the Yb:YAG thin-disk crystal is cooled by impinging water cooling at 20 °C.

The regenerative amplifier cavity is depicted in Fig. 1. The PC in the resonant cavity contains two BBO (both 8 mm × 8 mm × 25 mm in size) crystals. To accommodate the whole amplifier setup onto an optical experiment platform, the beam path must be folded many times. The broadened and amplified ns-level seed laser is injected into the regenerative amplifier cavity through the isolator, PC, seed beam spreading collimation system, Faraday rotator, and TFP. The 0° HR mirror M10 is mounted on a motorized mirror mount, controlled by an out-of-cavity piezoelectric controller (Thorlabs, KPZ101), which enables real-time position adjustment. The faint spot missed by the intracavity laser at the M10 position has been monitored by a position sensor (Thorlabs, DPD90A) placed behind the M10 to calibrate whether the intracavity laser transmission path has shifted. When the position sensor detects a change in the spot's position, it will send this data to the computer. The computer delivers the adjustment data to the piezoelectric controller, which subsequently controls the motorized mirror holder to continuously optimize M10's position. The piezoelectric control module is paired with a position sensor and computer-controlled to form a closed-loop system to ensure a stable operation of the regenerative amplifier. We determined the position of the motorized mirror holder by combining the closed-loop control effect of different positions, the adjustment range of the piezoelectric controller, and the reasonable positioning of optical components on the experimental platform.

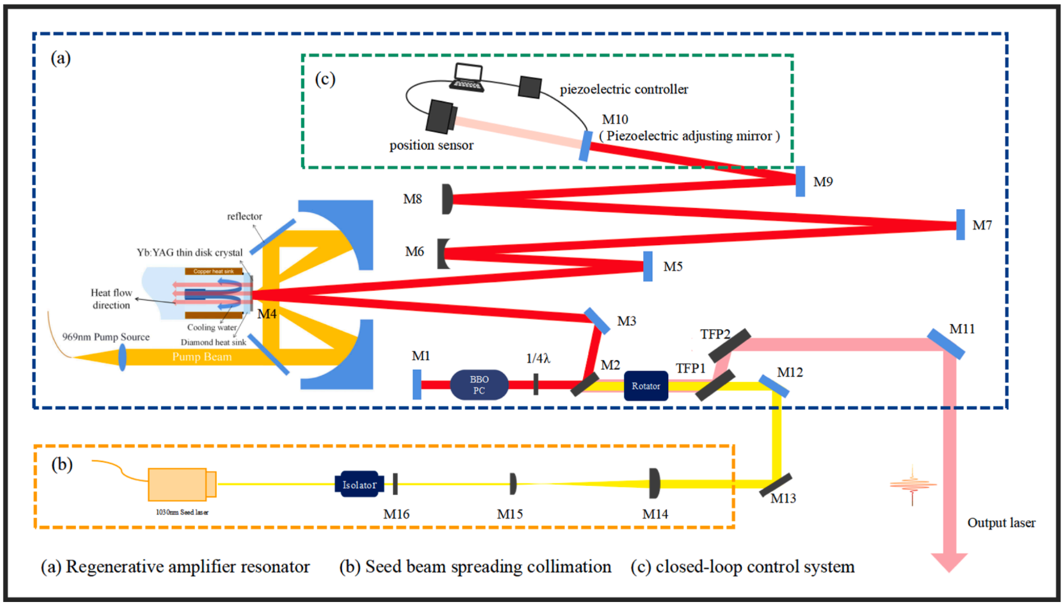

Fig. 1. Setup of the single thin-disk module regeneration amplifier. 0° reflectors (M1, M5, M7, M9, M10), 34° reflector M3, Yb:YAG thin-disk crystal M4, concave mirrors M6 with a radius of curvature of 8 m, and convex mirrors M8 with a radius of curvature of −5 m. They are integrated into a resonator of 6.9 m in length. The combination of concave (M6) and convex mirrors (M8) is used to achieve a relatively large beam diameter on the Yb:YAG thin disk.

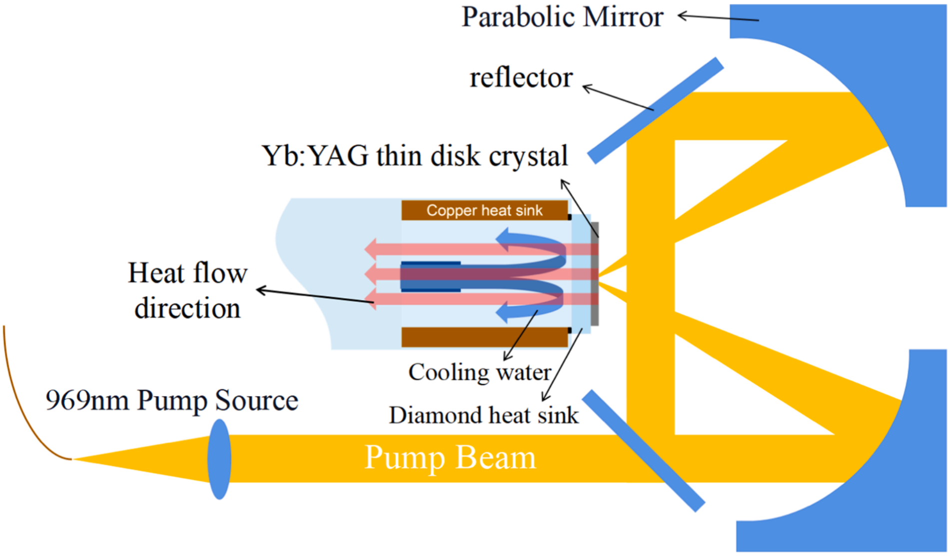

Fig. 2. Schematic diagram of the pump module of the thin-disk regeneration amplifier.

Simulation gives the radius distribution of the fundamental transverse mode spot inside the cavity, as depicted in Fig. 3. The resonator mode was calculated using the ABCD matrix formalism and was designed to satisfy a requirement to decrease the peak power on the optics. When the regenerative amplified laser passes through the PC and Yb:YAG thin-disk crystal, the spot becomes more extensive, which helps avoid damage to the components inside the cavity. It can improve the gain extraction efficiency by matching the spatial pattern of the pump laser on the Yb:YAG thin-disk crystal.

3. Results

Since the gain obtained from the seed laser varies with the number of round trips in the cavity and the gain saturation is reached after a long round trip in the cavity, it has been experimentally determined that 145 round trips (6709 ns round trip time in the cavity) are the suitable number of round trips for the system to output 201 W of stable power. Fig. 4(a) shows the average power of the output laser as a result of the pump power at different round trips in the cavity at a repetition rate of 50 kHz; the average power of the output laser can reach 201.4 W when the pump laser is increased to 962.4 W. When the number of seed laser round trips in the cavity is higher than or <145, gain saturation occurs at low power output due to intracavity losses, and seed light cannot be amplified efficiently. Fig. 4(b) shows the average output power of the regenerative amplifier as the pump laser increases. As the output power increases to 201 W and remains constant (Fig. 4(b) at 20 min), the voltage indicative of the piezoelectric control module that controls the pitch change of M10 slowly increases. The voltage stabilizes after 40 min (30–70 min in Fig. 4(b)). When the voltage remains constant, it indicates that the regenerative amplifier can operate stably in this state without closed-loop adjustment. The closed-loop system is primarily used to compensate for the spot shift induced by the thermal air wedge effect

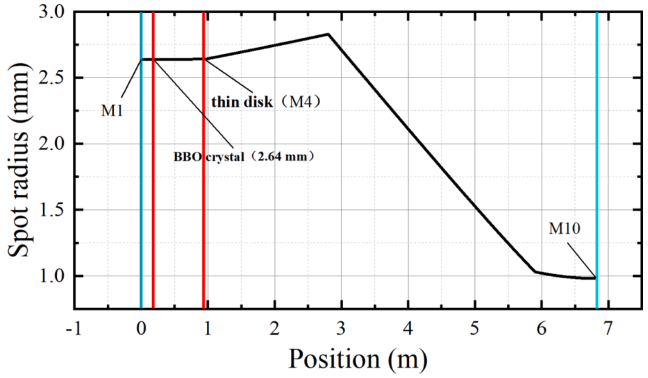

Fig. 3. Calculate the design mode of the resonator configuration. Spot size at different positions in the resonator, the vertical red lines denote positions of BBO crystal and Yb:YAG thin-disk crystal and the vertical blue lines denote positions of two end mirrors.

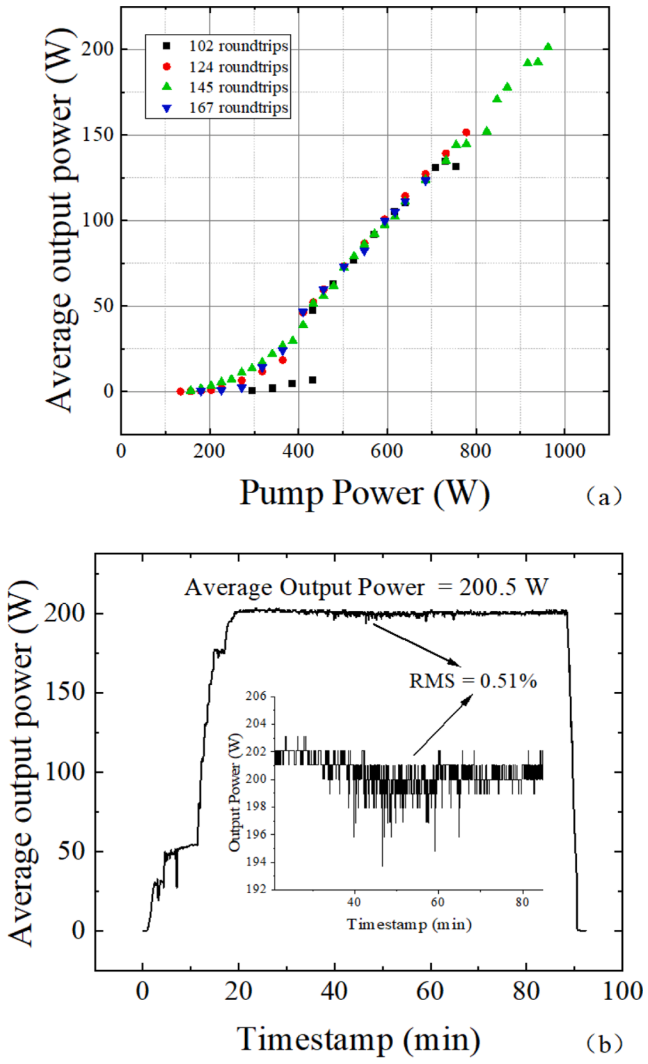

Fig. 4. The measurements were conducted using the Ophir 1000W-BB-34-V3 power meter at a repetition rate of 50 kHz. (a) The average power of the output laser with pump power for the different number of round trips of the seed laser in the cavity. At a 50 kHz repetition rate, a maximum output power of 201.4 W was achieved. (b) The output power of the regenerative amplifier at a repetition rate of 50 kHz Over 1 h, RMS = 0.51 %.

[27] and the unstable ambient airflow as output power increases. Once the system reaches thermal equilibrium, the output power becomes more stable, indicating that the laser crystal thermal lens effect and the hot air wedge effect significantly impact the regenerative amplifier's operation stability. During a period of about an hour, the output power stability RMS of 0.51 %.

At maximum output power, the CinCam CMOS – 1201 was used to measure the spot radius (1/e^2) and fit the beam quality factor M^2. As shown in Fig. 5, the beam quality factors of $M_x{}^2 = 1.08$ and $M_y{}^2 = 1.01$, indicate an excellent, almost diffraction-limited output beam. In contrast, the data of pulse duration, long-term stability, and spectral characteristics are all measured while the regenerative amplifier is operated at 201.4 W. The pulse bandwidth of the output beam is 1.28 ns (Fig. 6(a)), and the pulse amplitude stability is 2.78 % （RMS） over about 30 min. The center wavelength is 1031.7 nm, whereas the spectral breadth (FWHM) is 2.5 nm (Fig. 6(b)). Also, the measured output laser center wavelength and spectral width change varied with output power (Fig. 7), and it was discovered that the output laser center wavelength is essentially stable in different output power cases (The wavelengths are mainly distributed at 1031.4 nm and 1031.7 nm, which is due to the lower detector resolution) and the simultaneous observation of gain narrowing occurs at low power output. Fig. 7(b) shows that the gain narrowing mainly occurs during the laser's low power output period. In the 1997 report by C. Henninger et al. [28], gain narrowing was seen. This is due to different spectral components that have different gains and the restricted bandwidth of the gain medium.

4. Conclusion

In conclusion, we demonstrated a regenerative Yb:YAG thin-disk laser amplifier with 201 W of average output power at 50 kHz repetition rates. The amplifier can deliver this average output power over at least several hours, and output power fluctuation is 0.51 % (RMS) during a period of about an hour. The beam quality measurement at this average output power showed a near-diffraction-limited beam with $M_x{}^2 = 1.08$ and $M_y{}^2 = 1.01$. The optical-to-optical efficiency of up to 20.9 %, and a pulse duration of 1.28 ns at 1031.7 nm. The system presented here is a reliable amplification unit for a CPA, thanks to its high stability and excellent beam quality.

The improvement of the laser output power of the current ultrafast thin-disk regenerative amplifier is impacted by the cavity design. The

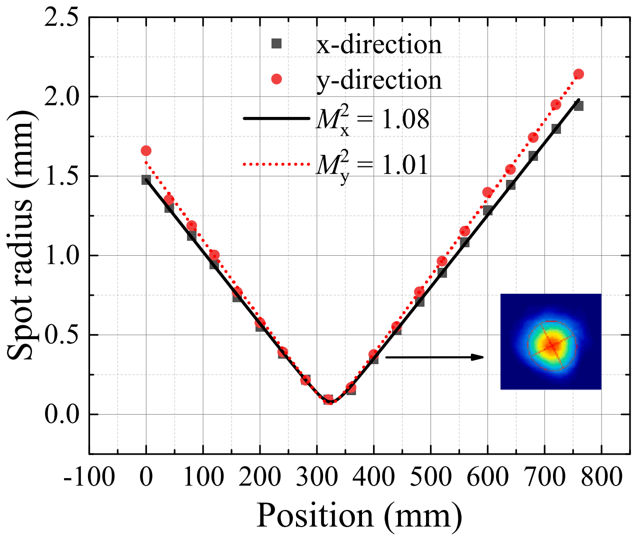

Fig. 5. The beam quality factor M^2 of the output laser measured at the average power of 201.4 W and a repetition rate of 50 kHz. The camera used for the test is CinCam CMOS – 1201.

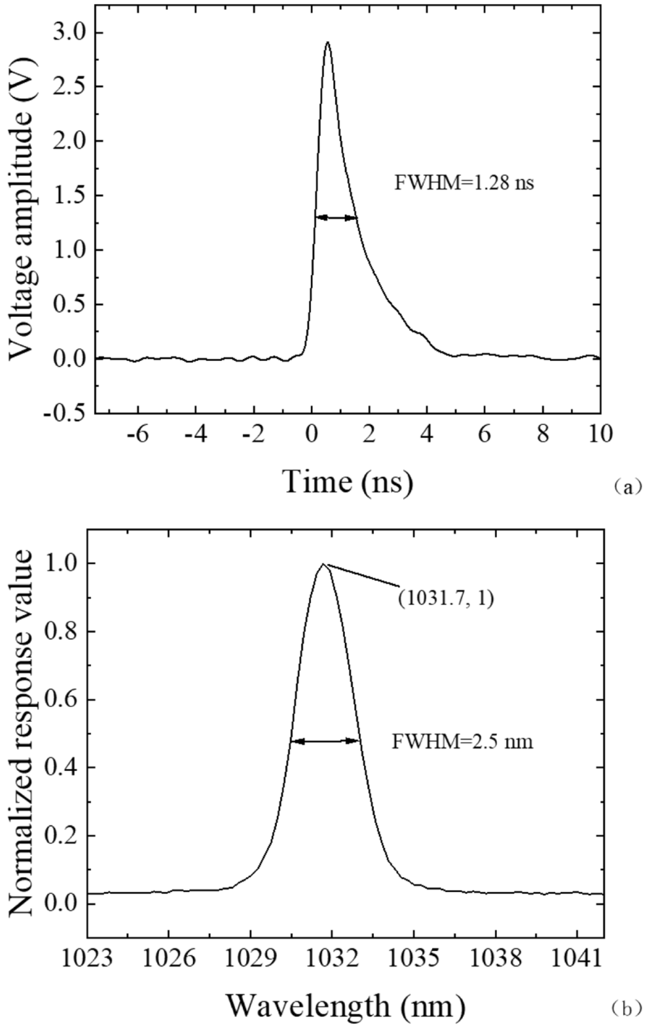

Fig. 6. Output laser characteristics were measured using a photodetector (EOT ET-3500), fiber optic spectrometer (OceanOptics HR400), and oscilloscope (Tektronix DPO 7354C). (a)When the average power is 201.4 W, the output light pulse width is 1.28 ns. (b) Output laser center wavelength of 1031.7 nm and spectral width of 2.5 nm.

damage threshold of the cavity components (especially the BBO crystal in the PC) is also a key reason for limiting further increases in output power. It is essential and urgent to improve the damage threshold of the BBO crystal. A further consideration for the thin-disk regenerative amplifier is how to improve its operating stability, which can be approached in different ways, such as reducing the optical path jitter caused by the external environmental influence, minimizing or resolving the thermal effect of the regenerative amplifier, and employing a cavity design that is both practical and efficient.

Funding

Innovation major project of Changchun Institute of Optics Fine Mechanics and Physics Chinese Academy of Sciences (No. E10302Y3M0); Jilin Province Youth Growth Science and Technology Program Project (No. 20220508041RC); Innovative Cross Team of the Chinese Academy of Sciences (No. JCTD-2020-13).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

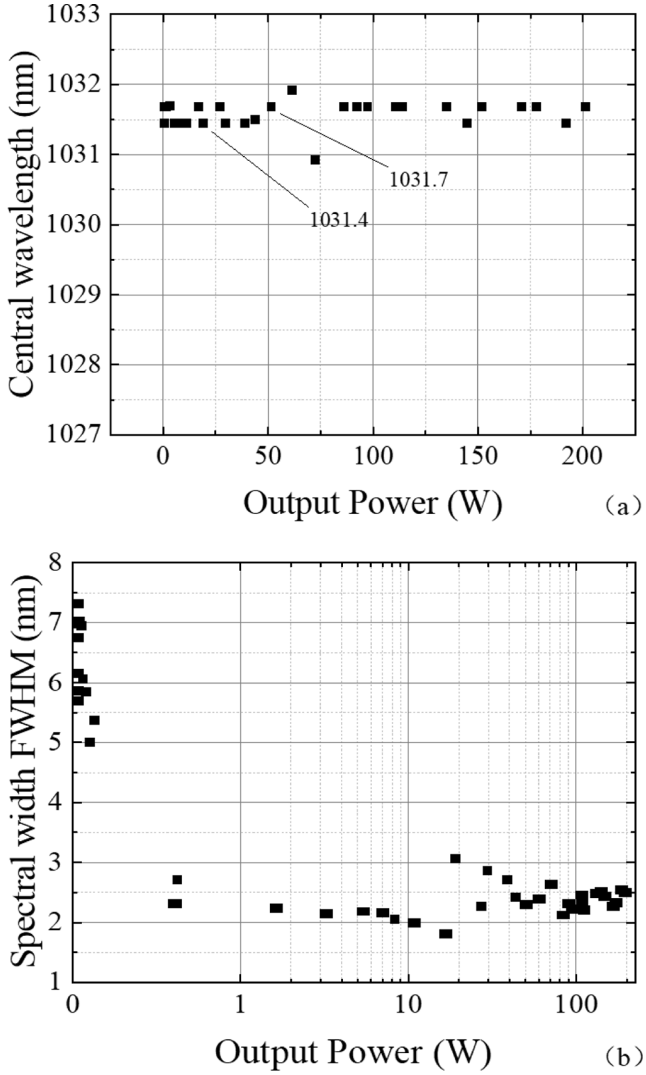

Fig. 7. Measured by a compound grating spectrometer HR4000CG-UV-NIR. Due to the detectors' limited resolution, the observed data can only be divided across some values, but valuable patterns can be observed. (a) The central wavelength of the output beam at different output power. (b) The spectral width of the output beam at different output power.

Data availability

Data will be made available on request.

References

[1] T.H. Maiman, Stimulated optical radiation in ruby, in: G. Laura, L. Tim (Eds.), A Century of Nature, University of Chicago Press, Chicago, 2003, pp. 113–114, doi: 10.7208/9780226284163-019.

[2] F.J. McClung, R.W. Hellwarth, Giant optical pulsations from ruby, Appl. Opt. 1 (S1) (1962) 103–105, https://doi.org/10.1364/AO.1.S1.000103.

[3] L.E. Hargrove, R.L. Fork, M.A. Pollack, Locking of He–Ne laser modes induced by synchronous intracavity modulation, Appl. Phys. Lett. 5 (1) (1964) 4–5, https://doi.org/10.1063/1.1754025.

[4] A. Mcpherson, G. Gibson, H. Jara, et al., Studies of multiphoton production of vacuum-ultraviolet radiation in the rare gases, J. Opt. Soc. Am. B 4 (4) (1987) 595–601, https://doi.org/10.1364/JOSAB.4.000595.

[5] D. Strickland, G. Mourou, Compression of amplified chirped optical pulses, Opt. Commun. 55 (6) (1985) 447–449, https://doi.org/10.1016/0030-4018(85)90151-8.

[6] A. Giesen, H. Hügel, A. Voss, et al., Scalable concept for diode-pumped high-power solid-state lasers, Appl. Phys. B 58 (5) (1994) 365–372, https://doi.org/10.1007/BF01081875.

[7] N. Thomas, K. Martin, U. Moritz, et al., 1kW, 200mJ picosecond thin-disk laser system, Opt. Lett. 42 (7) (2017) 1381–1384, https://doi.org/10.1364/OL.42.001381.

[8] W. Schneider, A. Ryabov, C. Lombosi, et al., 800-fs, 330-μJ pulses from a 100-W regenerative Yb:YAG thin-disk amplifier at 300kHz and THz generation in LiNbO3, Opt. Lett. 39 (23) (2014) 6604–6607, https://doi.org/10.1364/OL.39.006604.

[9] M. Schultze, E.M. Bothschafter, A. Sommer, et al., Controlling dielectrics with the electric field of light, Nature 493 (7430) (2013) 75–78, https://doi.org/10.1038/nature11720.

[10] T. Tajima, J.M. Dawson, Laser electron accelerator, Phys. Rev. Lett. 43 (4) (1979) 267–270, https://doi.org/10.1103/PhysRevLett.43.267.

[11] F. Salehi, A.J. Goers, G.A. Hine, et al., MeV electron acceleration at 1 kHz with <10 mJ laser pulses, Opt. Lett. 42 (2) (2017) 215–218, https://doi.org/10.1364/OL.42.000215.

[12] P.I. Abramov, E.V. Kuznetsov, L.A. Skvortsov, Prospects of using quantum-cascade lasers in optoelectronic countermeasure systems: review, J. Opt. Technol. 84 (5) (2017) 331–341, https://doi.org/10.1364/JOT.84.000331.

[13] M. Delaigue, C. Hönninger, R. Torres, et al., Comparative ultrafast laser source study for advanced materials processing, in: Proceedings of the Conference on Lasers and Electro-Optics 2012, San Jose, California, F 2012/05/06, Optica Publishing Group, 2012, doi: 10.1364/CLEO_AT.2012.ATu3L.6.

[14] C. Höiminger, G. Zhang, M. Moser, et al., Diode-pumped thin disc Yb:YAG regenerative amplifier, in: Proceedings of the Advanced Solid State Lasers, Coeur d'Alene, Idaho, F 1998/02/02, Optica Publishing Group, 1998, doi: 10.1364/ASSL.1998.TS3.

[15] D. Müller, S. Erhard, A. Giesen, Nd:YVO4 and Yb:YAG thin disk regenerative amplifier, in: Proceedings of the Conference on Lasers and Electro-Optics, Baltimore, Maryland, F 2001/05/06, Optica Publishing Group, 2001.

[16] C. Stolzenburg, A. Giesen, Picosecond regenerative Yb:YAG thin disk amplifier at 200 kHz repetition rate and 62 W output power, in: Proceedings of the Advanced Solid-State Photonics, Vancouver, F 2007/01/28, Optica Publishing Group, 2007, doi: 10.1364/ASSP.2007.MA6.

[17] C.Y. Teisset, M. Schultze, R. Bessing, et al., Picosecond thin-disk regenerative amplifier with high average power for pumping optical parametric amplifiers, in: Proceedings of the Conference on Lasers and Electro-Optics, F, 2013, doi: 10.1364/CLEO_SI.2013.CTh5C.6.

[18] R. Fleischhaker, R. Gebs, A. Budnicki, et al., Compact gigawatt-class sub-picosecond Yb:YAG thin-disk regenerative chirped-pulse amplifier with high average power at up to 800 kHz, in: Proceedings of the 2013 Conference on Lasers & Electro-Optics Europe & International Quantum Electronics Conference CLEO EUROPE/IQEC, F 12-16 May 2013, 2013, doi: 10.1109/CLEOE-IQEC.2013.6801054.

[19] S. Klingebiel, M. Schultze, C.Y. Teisset, et al., 220mJ, 1 kHz Picosecond regenerative thin-disk amplifier. In: Proceedings of the 2015 European Conference on Lasers and Electro-Optics - European Quantum Electronics Conference, Munich, F 2015/06/21, Optica Publishing Group, 2015, doi: 10.1364/CLEO_SI.2015.STu4O.2 .

[20] J. Novák, J.T. Green, T. Metzger, et al., Thin disk amplifier-based 40 mJ, 1 kHz, picosecond laser at 515 nm, Opt. Express 24 (6) (2016) 5728–5733, https://doi.org/10.1364/OE.24.005728.

[21] R. Jung, J. Tümmler, I. Will, Regenerative thin-disk amplifier for 300 mJ pulse energy, Opt. Express 24 (2) (2016) 883–887, https://doi.org/10.1364/OE.24.000883.

[22] T. Nubbemeyer, M. Kaumanns, M. Ueffing, et al., 1 kW, 200 mJ picosecond thin-disk laser system, Opt. Lett. 42 (7) (2017) 1381–1384, https://doi.org/10.1364/OL.42.001381.

[23] P. Krötz, C. Wandt, C. Grebing et al., Towards 2 kW, 20 kHz ultrafast thin-disk based regenerative amplifiers, in: Proceedings of the Laser Congress 2019 (ASSL, LAC, LS&C), Vienna, F 2019/09/29, Optica Publishing Group, 2019, doi: 10.1364/ASSL.2019.ATh1A.8.

[24] C. Herkommer, P. Krötz, S. Klingebiel, et al., Towards a joule-class ultrafast thin-disk based amplifier at kilohertz repetition rate, in: Proceedings of the 2019 Conference on Lasers and Electro-Optics (CLEO), F 5-10 May 2019, 2019, doi: 10.1364/CLEO_SI.2019.SM4E.3.

[25] D. Jing, C. Hantian, W. Hailin, et al., Research on picosecond laser regenerative amplifier based on thin-disk gain medium, Acta Opt. Sin. 41 (14) (2021) 8, https://doi.org/10.3788/AOS202141.1414003.

[26] J. Guo, Z. Gao, D. Sun, et al., An efficient high-power femtosecond laser based on periodic-layered-Kerr media nonlinear compression and a Yb:YAG regenerative amplifier, High Power Laser Sci. Eng. 10 (2022) e10.

[27] A. Diebold, F. Saltarelli, I.J. Graumann, et al., Gas-lens effect in kW-class thin-disk lasers, Opt. Express 26 (10) (2018), https://doi.org/10.1364/OE.26.012648.

[28] C. Hönninger, I. Johannsen, M. Moser, et al., Diode-pumped thin-disk Yb:YAG regenerative amplifier, Appl. Phys. B 65 (3) (1997) 423–426, https://doi.org/10.1007/s003400050291.