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Realization of thermally-near-unstable resonator thin-disk laser and compensation of air wedge effect

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ABSTRACT

This paper reports on a Yb: YAG thin-disk laser based on a thermally-near-unstable resonator. The cavity length of the resonator is 3 m, which is 3.5 m less than the cavity length of a stable resonator, simplifying the oscillator structure and reducing the optical loss of the resonator cavity. The disk laser based on a thermally-near-unstable resonator achieves a laser output power of 38.3 W with beam quality approaching the diffraction limit. The laser center wavelength is 1.03 μm. The resonator becomes misaligned during the increase in pump power due to air convection, reducing laser output power. In this paper, one end mirror of the thermally-near-unstable resonator is replaced with a *retro*-reflector to compensate for the misalignment of the resonator. The laser output power of the resonator with *retro*-reflector increased to 81 W. The beam quality M^2 factors in the × and y directions are 1.03 and 1.14, respectively. retro-reflector significantly improves the operational stability of the laser.

1. Introduction

As an essential branch of solid-state lasers, thin-disk lasers can achieve high-power continuous wave laser and high pulse energy pulsed laser output[1–3]. It has significant advantages in realizing high repetition rate, high pulse energy, and ultra-short pulse laser, mainly realized by regenerative amplifiers and multi-pass amplifiers [4,5]. One of the regenerative amplifier's cores is the amplifier resonator's design. A resonator with a short cavity length and large fundamental mode volume is more conducive to amplifying high-energy lasers. A thermally-near-unstable resonator can satisfy this requirement[6]. The design of a thermally-near-unstable resonator with a cavity length of 3 m is based on a thin-disk crystal, which has good heat dissipation and a weak thermal lens effect. Compared to a stable resonator, a thermally-near-unstable resonator operates at the edge of the stable region, has a larger fundamental mode spot on the thin-disk, and has greater loss to higher order transverse modes, enabling high power, good beam quality fundamental mode laser output. The thermally-near-unstable resonator has a simple structure, low loss, and large mode volume, which requires a lower damage threshold for the end mirror.

When the temperature of the thin-disk rises, the air convection generated in front of the thin-disk causes a misalignment of the resonator cavities, a phenomenon known as the air wedge effect[7]. A resonator with a corner cone as an end mirror effectively solves the problem of resonator detuning. However, the corner cone will change the polarization state of the output laser[8,9]. Tom Dietrich et al. used a grating to compensate passively for resonator misalignment, but this compensation method changes the wavelength of the output laser[10]. Christoph Röcker et al. used a *retro*-reflector to compensate for the air wedge effect and achieve a 2 kW average ultrafast laser output[11]. However, the above work does not apply the *retro*-reflector to the resonator to compensate for the misalignment of the disk laser oscillator.

This paper compensates for the air wedge effect of using a *retro*-reflector. Comparing the laser output characteristics of a thermally-near-unstable resonator with and without the *retro*-reflector verified the compensation effect of the *retro*-reflector. We replaced one of the end mirrors of the resonator with a *retro*-reflector. The same simulation and experiment found that the *retro*-reflector has a good compensation effect on the air wedge effect. The resonator with *retro*-reflector can obtain higher power and better stability output laser in the experiment.

The output laser power of the thermally-near-unstable resonator with a cavity length of 3 m was 38.3 W, and the beam quality was near

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the diffraction limit. The output power of the resonator with a *retro*-reflector reaches 81 W, and the beam quality M^2 factors in the × and y directions are 1.03 and 1.14, respectively. The experimental results show that the *retro*-reflector effectively compensates for the resonator misalignment caused by air convection and improves the stability of the resonator.

2. Design and simulation

2.1. Design of thermally-near-unstable resonator

The resonator cavity can be divided into stable and unstable resonators according to the geometric deflection loss in the cavity. A cavity's total transformation matrix of paraxial light is expressed in matrix *T* [12,13].

$$T = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \tag{1}$$

The stability condition of the cavity is related to the trace of the transformation matrix *T*. Whether the resonator is stable or unstable is determined by inequality. (2).

$$-1 < \frac{1}{2}(A + D) < 1 \tag{2}$$

The resonator is stable when the resonator cavity (A + D)/2 satisfies the equation (2) condition. Otherwise, the resonator is unstable.

When designing the resonator, it is necessary to consider the influence of the thin-disk diopter change on the laser mode in the resonator. As the pump power increases, the thin-disk crystal's thermal lens effect changes the thin-disk crystal's diopter. Therefore, measuring the diopter of the thin-disk crystal is very important for the resonator's design. A wavefront sensor measured the diopter of the thin-disk in fluorescence mode and laser output mode. Fig. 1 shows the measurement results. When the pump power increased from 0 W to 1000 W, the diopter of the thin-disk varied from 0.005 m^{-1} to −0.02 m^{-1} in fluorescence mode and from 0.005 m^{-1} to −0.005 m^{-1} in laser output mode. Output laser mode is the multi-transverse mode.

The gain medium in the resonator is a Yb: YAG thin-disk crystal. The radius of the pump spot on the thin-disk is 3.2 mm. When designing the resonator cavity, the radius of the fundamental mode spot on the disc is 70 % to 80 % of the radius of the pump spot[14], and the corresponding fundamental mode spot radius ranges from 2.24 to 2.56 mm. We designed a 3 m cavity length thermally-near-unstable resonator according to the range of variation of the thin-disk diopter. When the diopter of the thin-disk is −0.0066 m^{-1}, the (A + D)/2 of the resonator is 0.93, and the radius of the fundamental mode spot on the thin-disk is 2.56 mm. The black dashed line in Fig. 2(a) shows the distribution of the fundamental mode in the resonator.

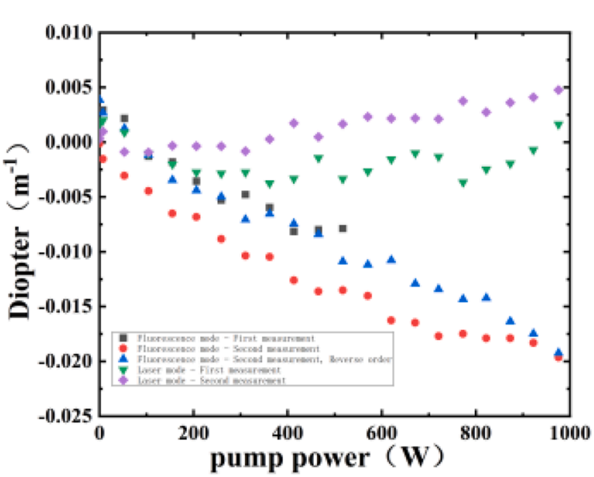

Fig. 1. Variation of disc optical focal length with pump power.

When designing the resonator cavity, the radius of the fundamental mode spot on the thin-disk is simulated numerically with the change of the diopter of the thin-disk, as shown in the U-shaped curve in Fig. 2 (b). When the resonator cavity runs at the bottom of the U-shaped curve, the size of the fundamental mode on the thin-disk is almost constant, and this region is known as the thermally stable region. However, at this point, the fundamental mode spot size on the thin-disk is smaller, the higher order transverse mode diffraction loss is lower and easier to oscillate, and the resonator will produce a multi-mode laser output. As the thin-disk's diopter decreases, the resonator work region moves along the U-shaped curve towards the edge of the left-hand stability zone. At this point, the radius of the fundamental mode spot on the thin-disk increases, and the higher-order transverse mode loss is significant. The laser can obtain a high power and high beam quality laser output. The resonant cavity running at the edge of the stable region is called the thermally near-unstable resonator. Our design of the thermally-near-unstable runs in the region surrounded by the black dashed line in Fig. 2(b).

To understand the advantages of a thermally-near-unstable resonator, we designed a stable resonator to compare it. Under the condition of equal spot size of the fundamental mode on the thin-disk, the cavity length is 3.5 m longer than the cavity length of the thermally-near-unstable resonator. The solid red line in Fig. 2(a) shows the distribution of the fundamental modes in the stable resonator. The minimum spot radius is 1.98 mm in the thermally-near-unstable resonator and 1.21 mm in the stable resonator.

2.2. Retro-reflector compensation for air wedge effect

2.2.1. Simulation of a thermally-near-unstable cavity with retro-reflector

Air convection causes a misalignment of the resonator cavity in a thin-disk laser. To correct the misalignment of the resonator, we used a *retro*-reflector to replace one of the end mirrors of the thermally-near-unstable resonator. When the diopter of the thin-disk is −0.0066 m^{-1}, the radius of the fundamental mode spot on the thin-disk is 2.525 mm, and (A + D)/2 of the resonator is 0.71. Fig. 3(a) shows the distribution of the fundamental mode spot in the resonator. Comparing Fig. 2(a) with Fig. 3(a) finds that when the diopter of the thin-disk is identical, the radius of the fundamental mode spot on the thin-disk is the same in the resonator cavity with and without the *retro*-reflector.

Fig. 3(b) shows the variation of the radius of the fundamental mode spot at the thin-disk in the resonator cavity with a *retro*-reflector. The resonator cavity still runs on the left edge of the U-shaped curve within the variation of the diopter of the thin-disk, indicating that the resonator cavity with the *retro*-reflector is still a thermally-near-unstable resonator. As seen from the simulation results in Fig. 3, replacing one of the end mirrors in the thermally near unstable resonator with a *retro*-reflector does not affect the resonator's laser output characteristics, which clearly shows the correction effect of the *retro*-reflector on the resonator. For pulsed light, the expanded intracavity spot facilitates the laser to achieve a higher energy laser output. In terms of end-mirror damage threshold, a thermally-near-unstable resonator is 2.68 times higher than a stable resonator.

2.2.2. Simulation of the air wedge effect

Using the ray tracing method in geometric optics simulated the effect of the air wedge on the resonator. We simulated the propagation of a Gaussian beam in a resonator cavity with and without a *retro*-reflector. We placed an air wedge vertically and a 10 mm × 10 mm rectangular image detector in front of the disk. The wedge angles of the air wedge were set to 0°, 5°, 10°, and 15° to observe the deviation of the fundamental mode spot on the thin-disk. Fig. 4 shows the simulation results. Both resonators are free of misalignment when the air wedge is 0°. When the angle of the air wedge increases to 5°, there is no misalignment in the

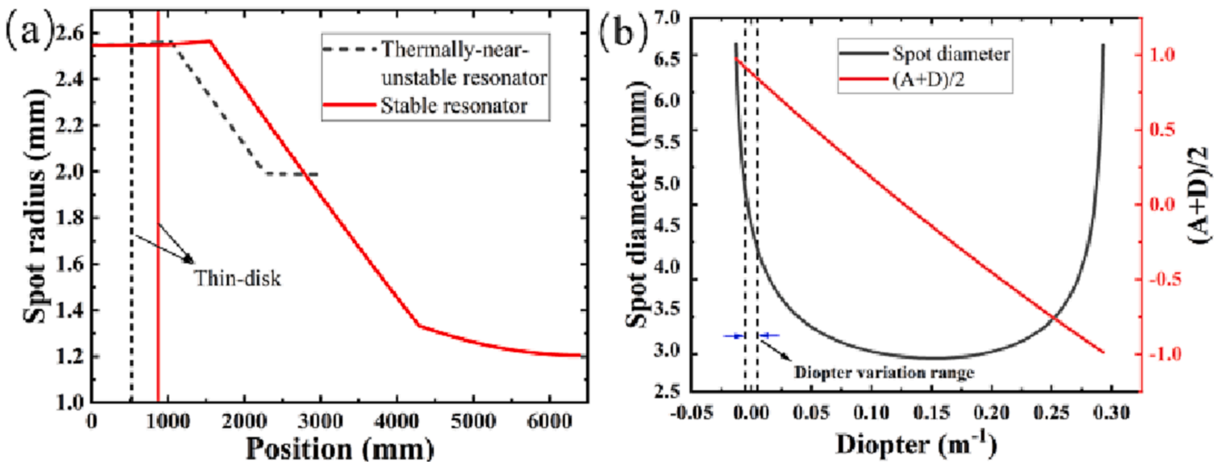

Fig. 2. (a) Fundamental mode spot distribution in the stable resonator and thermally-near-unstable resonator. (b) Variation of the radius of the fundamental mode spot on the thin-disk and the (A + D)/2 of the resonator with the diopter of the thin-disk.

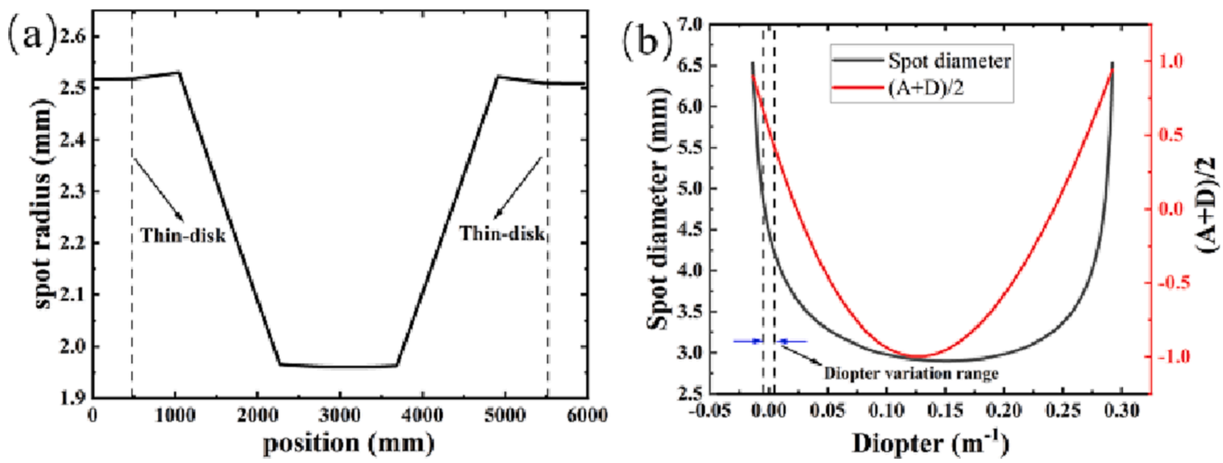

Fig. 3. (a) Fundamental mode spot distribution in resonator with *retro*-reflector. (b) Variation of the radius of the fundamental mode spot on the thin-disk and the (A + D)/2 of the resonator with the diopter of thin-disk.

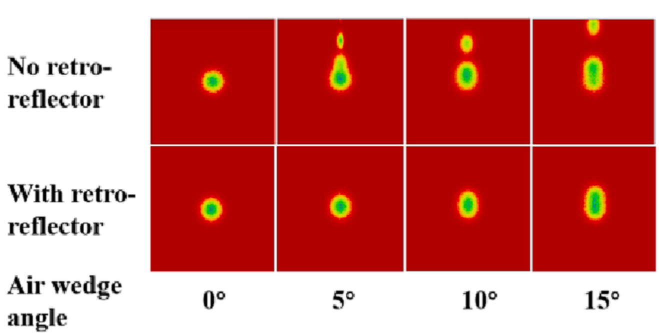

Fig. 4. Position of the laser spot on the thin-disk in the resonator with and without the *retro*-reflector at different air wedge angles.

resonator with the *retro*-reflector. However, the resonator without the *retro*-reflector produces a significant misalignment. When the air wedge angle increases to 15°, the resonator with *retro*-reflectors also becomes misaligned. It shows that replacing one of the end mirrors of the resonator with a *retro*-reflector can effectively compensate for the misalignment of the resonator caused by the air wedge within a certain range.

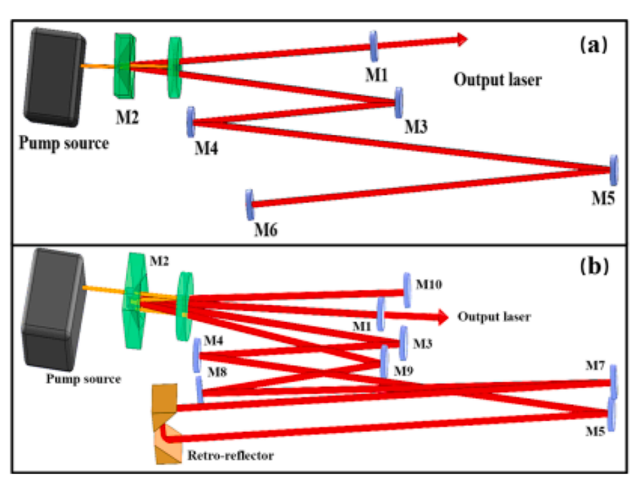

Fig. 5. (a) Structure diagram of thermally-near-unstable resonator. (b) Structure diagram of resonator with *retro*-reflector.

3. Results and discussion

3.1. Experimental setup

Based on the simulation, we carried out verification experiments. Fig. 5(a) shows the schematic diagram of the structure of a thermally-near-unstable resonator with a cavity length of 3 m. M1 is an output mirror with a transmittance of 2.4 %, and M2 is a Yb: YAG thin-disk with a base mode spot radius of 2.56 mm. M3 is a concave mirror with a radius of 10 m, M4 is a planar reflection mirror, M5 is a convex mirror with a radius of −9 m, and M6 is a planar mirror. The central wavelength of the pump light is 969 nm.

To verify the compensation effect of the *retro*-reflector, we built a resonator with a *retro*-reflector, as shown in Fig. 5(b). Based on Fig. 5(a), the end mirror M6 in the thermally-near-unstable resonator is replaced with a *retro*-reflector, M7 is a convex mirror with a radius of curvature of −9 m, M8 is a planar reflector, M9 is a concave mirror with a radius of curvature of 10 m, and M10 is a planar mirror.

3.2. Experimental results

3.2.1. Experimental results of the thermally-near-unstable resonator

In this paper, we first carried out the thermally-near-unstable resonator experiments. As shown in Fig. 5(a), an experimental optical path was built. We adjusted the resonator at an output power of about 30 W. Then the pump power was reduced to 0 W. After that, the pump power increased from 0 W. we didn't adjust the resonator during the pump power increase. During laser output, we used a camera to record the change of the laser spot position on the thin-disk. Fig. 6(a) shows the variation of the output laser power with the pump power, and the highest power of the output laser is 38.3 W for the thermal near unstable resonator at the pump power of 310 W. The beam quality of the output laser is measured using the CMOS camera at this power, as shown in Fig. 6(b). The beam quality M^2 factor in both the × and y directions is less than 1.1. The output laser mode is always fundamental in increasing the pump power. A thermally-near-unstable resonator with a thin-disk as the gain medium can achieve good beam-quality laser output.

The illustration in Fig. 6(a) shows the deviation of the laser spot on the thin-disk during the pump power increase. When the laser extracts the thin-disk's stored energy, the extracted area's fluorescence becomes weaker, so the shaded part in the illustration represents the location of the laser spot. As the pump power increases, the laser spot gradually deviates from the center of the pump region. When the pump power reaches 360 W, the laser spot on the thin-disk is at the upper left of the pump region. The output laser power drops to 26.3 W. Fig. 6(c) shows the variation of the output laser power with time, which fails to achieve stable operation during the power increase.

3.2.2. Experimental results of the thermally-near-unstable resonator with retro-reflector

To verify the correction effect of the *retro*-reflector in the resonant cavity, we chose to compensate for the laser deflection in the vertical direction. Based on the thermally-near-unstable resonator, a *retro*-reflector replaced one of the end mirrors of the resonator. Fig. 4(b) shows the resonator with a *retro*-reflector. The laser output power of the resonator with *retro*-reflector varies with the pump power, as shown in Fig. 7(a), and the laser output power is 81 W at the pump power of 465 W. The laser spot on the thin-disk shifted to the left. The laser spot does not move significantly in the vertical direction. The output power of the laser is improved by 42.7 W compared with the thermally-near-unstable resonator. Fig. 7(b) shows the beam quality of the output laser, and the beam quality M^2 factors in the × and y directions are 1.03 and 1.14, respectively. Fig. 7(c) shows the variation of output power with time for the resonator with a *retro*-reflector. When the laser output power is 81 W, the laser can operate more stably, and the power drops from 81 W to 60 W after 10 min. The stability is improved compared with the thermally-near-unstable resonator. The thin-disk's laser spot appeared shift to the left, causing the laser power to drop.

The experimental results comparing the resonator without and with *retro*-reflectors show that adding *retro*-reflectors compensates for the resonator misalignment caused by the air wedge. A resonator with a *retro*-reflector enhances the stability of the laser without changing the output characteristics of the laser.

3.3. Discussion

Due to the misalignment of the resonator, the maximum output power obtained by the thermally- near-unstable resonator is 81 W. If the resonator misalignment caused by the air wedge effect can be completely compensated, the thermally-near-unstable cavity gain medium based on the disc can achieve higher laser output power than 81 W. At the pump power below 1000 W, the thin disk used in the experiment can meet the operation requirements of the thermally-near-unstable resonator. However, the thermal effect of the resonator under high-power operation will affect the stability of the laser. The thermal lensing effect of the thin-disk becomes more severe with a further increase of pump power, making the thermally-near-unstable resonator become an unstable resonator. The thin-disk laser will have the problems of increasing loss, decreasing output power, and deteriorating beam quality. If the thermal effect of the thin-disk laser can be better managed, the thermally-near-unstable resonator will be more widely used. The pulsed pumping approach can effectively decrease the thermal effect of the thin-disk, and the thermally-near-unstable resonator has advantages in pulsed laser amplification and pulsed laser generation.

In the experiment, the *retro*-reflector compensated the laser deviation in the vertical direction well, but the laser deviation in the horizontal direction existed both before and after compensation, indicating that the deviation in the horizontal direction was independent of the deviation in the vertical direction. The air wedge effect in the horizontal direction and the change of the disk surface shape are both possible causes of the horizontal misalignment of the laser. The next step of the study is to analyze and determine the causes of the laser deviation in the

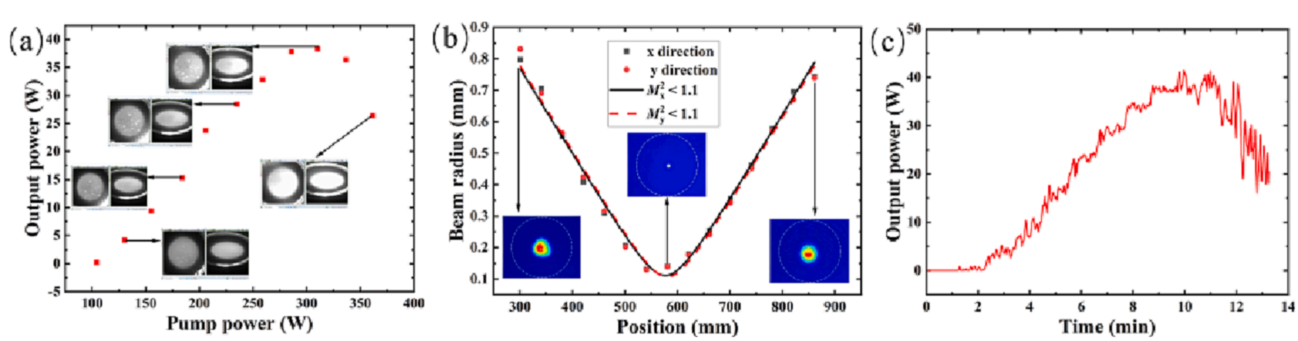

Fig. 6. (a) Variation of output power with time. (b) Beam quality. (c) Variation of output laser power with time.

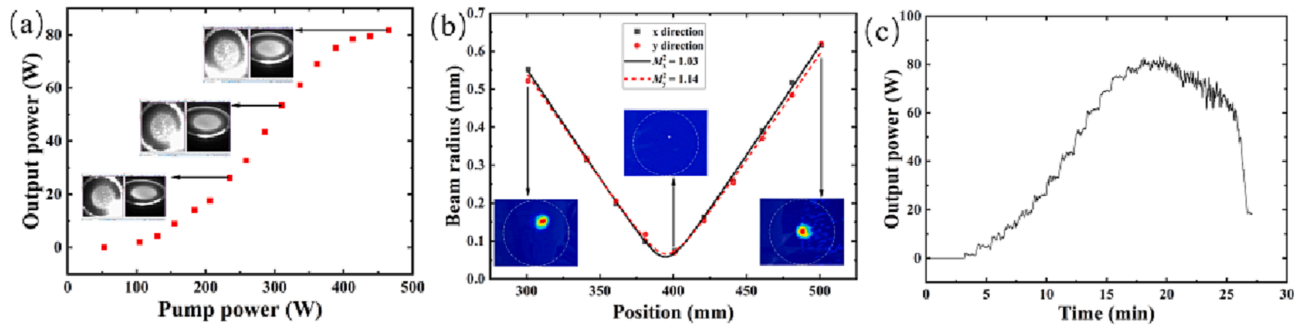

Fig. 7. (a) Variation of output power with time. (b) Beam quality. (c) Variation of output laser power with time.

horizontal direction and improve the design of the *retro*-reflector to obtain better compensation.

4. Conclusion

In this paper, a thermally-near-unstable resonator is designed based on a disk gain medium, and the laser output characteristics of the thermally-near-unstable resonator are obtained experimentally. The thermally-near-unstable resonator achieves a fundamental mode laser output with a power of 38.3 W near the diffraction limit. The highest laser output power of 81 W was obtained experimentally for the resonator with a *retro*-reflector. The beam quality M^2 factors in the × and y directions were 1.03 and 1.14, respectively. According to this experimental result, it can be found that the thermally-near-unstable resonator has a larger fundamental mode volume and the minimum spot in the resonator is larger than that of the stable resonator. The thermally-near-unstable resonator based on the thin-disk gain medium can be used to achieve high energy amplification of ultrashort pulse lasers, such as regenerative amplifiers.

The thermally-near-unstable resonator misaligned during the laser output due to the air wedge effect. The laser spot on the thin-disk gradually deviates from the pumping region, reducing laser output power. To compensate for the air wedge effect, we used a *retro*-reflector to replace one of the end mirrors of the thermally-near-unstable resonator.

We simulated the stable region of a resonator without and with a *retro*-reflector. The changing trend of the size of the fundamental mode spot on the thin-disk in the two resonators is consistent with the diopter of the thin-disk. The simulation found that resonator with a *retro*-reflector has enhanced anti-detuning capability.

The compensation effect of the *retro*-reflector on the air wedge effect was verified experimentally by observing the deviation of the output laser power from the laser spot on the thin-disk without adjusting the resonator to increase the pump power. The maximum power of the fundamental mode laser output from the thermally-near-unstable resonator is 38.3 W. The laser spot on the thin-disk is shifted to the upper left of the pumping region. In comparison, the maximum power of the fundamental mode laser output from the resonator with *retro*-reflector is 81 W. The laser spot on the thin-disk is shifted to the left of the pumping region. The resonator with *retro*-reflection can achieve more stable operation in 10 min, but the thermally-near-unstable resonator cannot achieve stable operation. Experiments indicate that the *retro*-reflector can passively compensate for the shift of the laser spot in the vertical direction.

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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.

Data availability

Data will be made available on request.

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