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High-Power, High-Beam-Quality, Long-Pulse-Width 532 nm Laser Based on a 4f Optical System

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Abstract: In response to the demand for high-power, long-pulse-width 532 nm lasers in the medical and industrial processing fields, this paper explains how the laser cavity of a high-power Nd:YAG 532 nm laser can be extended while maintaining the laser's q-parameter by using a 4f optical system. The results show that at a repetition rate of 10 kHz, the extended cavity achieved a maximum average power of 112 W. Compared with the short cavity, the power was not significantly reduced. The pulse width was extended from 56 ns to 85 ns, and its broadening ratio reached 46.5%. The laser maintained good beam quality during high-power operation.

Keywords: Nd:YAG; acousto-optic Q-switched; intracavity frequency doubling; 4f optical system; long pulse width

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1. Introduction

High-power 532 nm lasers are widely used in laser machining [1], medical laser treatments [2], and laser displays [3] due to their high efficiency, stability, and output energy. For specific applications, such as laser welding, adjustments and optimizations based on the material properties are necessary to achieve the best welding results. By adjusting the laser's output pulse width, the degree of material melting and heating depth can be controlled, allowing for more precise parameter control [4]. In laser medical applications, the differences in skin tissue composition and characteristics require the selection of an appropriate laser output pulse width based on the patient's skin type and condition [5].

Therefore, researching long-pulse all-solid-state 532 nm lasers is of great significance. In Q-switched lasers, the pulse width is determined by parameters such as gain, loss, and cavity length. The most effective method for tuning pulse width in such lasers is to adjust the cavity length, thereby increasing the output laser pulse width and achieving tunable pulse widths. In 2002, Jun Kojima from NASA's Glenn Research Center used three ring cavities to achieve simple passive long nanosecond pulse laser stretching, converting input laser pulses of 2.8 ns to output pulses of 75 ns with a conversion efficiency of 83% [6]. In 2018, Simon Chard and colleagues from Andritz Powerlase in the UK proposed a 400 W Q-switched 532 nm laser that controls pulse width and pulse shape by varying the repetition frequency and trigger delay of each cavity's Q-switch, as well as adjusting the delay and attenuation of each cavity. By extending the cavity length, the pulse duration was increased from 66 ns to 140 ns at a repetition rate of 8 kHz without significant power loss, though the

beam quality was poorer with an $M^2 < 30$ [7]. In 2019, Yan-Jie Song and colleagues from the Institute of Physical Chemistry, Chinese Academy of Sciences, used a multi-pass cavity (MPC) combined with pump power technology to achieve adjustable pulse widths ranging from 160 to 1000 ns at a repetition rate of 10 kHz. At a pulse width of 560 ns, they achieved an output power of 10.6 W with a beam quality factor of $M^2 = 1.45$ [8].

Nd:YAG is one of the most commonly used solid-state laser materials. Due to the excellent match between Nd:YAG's activation ions and the LD (laser diode) emission spectrum, along with its narrow fluorescence line and good physical and mechanical properties, it is highly favorable for laser generation. Using Nd:YAG as the laser medium allows for high-gain, low-threshold lasers and is suitable for high-energy pumping, which helps in achieving high optical quality. Consequently, Nd:YAG lasers pumped by an LD are the most common DPL devices [9–11]. In the frequency doubling of Nd:YAG lasers, KTP (Potassium Titanyl Phosphate) and LBO (Lithium Triborate) crystals are the most frequently used doubling crystals. KTP crystals are widely used due to their excellent properties and large non-linear coefficient. However, KTP crystals have some limitations, including a relatively low damage threshold, making them susceptible to damage under high cavity power density. Additionally, after long-term operation, KTP crystals may develop gray spots, increasing loss and reducing laser output power. In contrast, LBO crystals have a significantly higher damage threshold, making them better suited for high-power lasers and reducing the risk of crystal damage. Moreover, LBO crystals have lower hygroscopicity and are less prone to issues like gray spots. Thus, in high-power green laser systems, selecting LBO crystals for frequency doubling can effectively enhance the performance and reliability of the laser [12].

The q-parameter of a Gaussian beam is used to describe the physical properties of the beam during propagation, including amplitude distribution, phase distribution, and spot size. As the Gaussian beam propagates through space, its q-parameter changes accordingly. This parameter is useful for characterizing the propagation behavior of the beam in free space or optical systems. Maintaining a constant q-parameter for a laser beam is of great significance, as it implies that the beam's focal length, divergence properties, and spatial distribution remain stable [13]. This stability allows for precise control and stable transmission of the beam, ultimately leading to higher beam quality and output power. A 4f optical system, consisting of just two lenses with a distance between them equal to twice the focal length of each lens, can be applied to all-solid-state 532 nm lasers. It enables pulse width broadening while maintaining the q-parameter of the Gaussian beam.

This paper first extends the laser resonator on the basis of a Nd:YAG 532 nm laser with double acousto-optic Q-switching and LBO frequency doubling, using a 4f optical system while maintaining the laser's q-parameter. The results show that, at a repetition rate of 10 kHz, the extended cavity achieves a maximum average power of 112 W, with a decrease of less than 10 W compared to the short cavity. The pulse width is extended from 58 ns to 85 ns with an average power of 108 W, the beam quality in the horizontal and vertical directions are $M_x^2 = 15.76$ and $M_y^2 = 14.25$, respectively.

2. Theoretical Analysis

A basic 4f optical system is shown in Figure 1. Its basic structure consists of the following five parts: (1) an input plane where the optical information to be processed (such as an image or beam) is placed; (2) a lens L_1 with a focal length of f_1, which performs a Fourier transform of the light field distribution on the input plane; (3) a Fourier plane, located at the focal plane of the first lens, where the Fourier transform of the input light field is formed; (4) a lens L_2 with a focal length of f_2, which performs a Fourier transform of the light field that has been Fourier-transformed, recovering it to the spatial domain; (5) an output plane located at the focal plane of the second lens, where the processed optical information is displayed. In a 4f optical system, after passing through the first lens, the input light field forms its Fourier transform at the Fourier plane. Optical filters placed at the Fourier plane can modulate specific spatial frequency components. After passing through

the second lens, the modulated light field at the Fourier plane is Fourier-transformed again, forming the output light field. The name "4f system" comes from its structure. If the focal length f_1 of L_1 is equal to the focal length f_2 of L_2, and the distance between them is exactly twice their focal length, the entire system's distance is 4f, which is a standard 4f system where the image and object field regions are at a 1:1 ratio. This configuration can be used for spatial filtering [14], digital image processing [15], and amplification of laser beams [16]. In such a system, it is crucial to correctly choose the focal lengths and positions of the lenses, while ensuring the lenses are stable and the optical axis is aligned, to avoid aberrations and beam distortions. This ensures that the 4f system functions as an image transfer system without introducing degradation in beam quality, and maintains the q-parameter of the input and output beams unchanged [17].

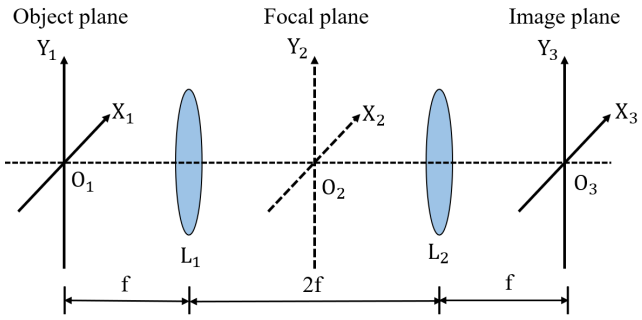


Figure 1. 4f optical system diagram.

When the number of particles in the upper energy level exceeds the threshold, laser oscillation occurs. As particles in the upper level are consumed, the inversion number decreases, and oscillation stops when it falls below the threshold. Continuous pumping accumulates particles in the upper level, and once the threshold is exceeded again, a second pulse is generated, repeating this process until the pumping stops. Each pulse peak is low because it's generated near the threshold, and increasing the pumping energy only increases the number of small peaks. To enhance the peak power of the pulse, it's necessary to accumulate a large number of particles in the upper level. This can be achieved by setting the laser's threshold very high to suppress oscillation, allowing particle accumulation. When the inversion number reaches its maximum, suddenly lowering the threshold causes the accumulated particles to transition rapidly to the lower level, releasing energy in a very short time and producing a high peak power giant pulse laser output.

The oscillation threshold condition of the laser can be expressed as:

$$\Delta n_{th} \geq \frac{g}{A_{21}} \cdot \frac{1}{\tau_c} \tag{1}$$

where,

$$\tau_c = \frac{Q}{2\pi\nu} \tag{2}$$

Therefore,

$$\Delta n_{th} \geq \frac{g}{A_{21}} \cdot \frac{2\pi\nu}{Q} \tag{3}$$

In the equation, g represents the number of modes, A_{21} is the spontaneous emission probability, and τ_c is the photon lifetime in the cavity. Q is called the quality factor, which is defined as:

$$Q = 2\pi\nu_0 \left(\frac{\text{Stored energy in the cavity}}{\text{Energy loss per second}} \right) \tag{4}$$

In the equation, ν_0 is the central frequency of the laser.

The calculation formula for the quality factor Q is [18]:

$$Q = 2\pi\nu_0 \left(\frac{W}{\frac{\delta WC}{nL}} \right) = \frac{2\pi nL}{\delta\lambda_0} \tag{5}$$

In the formula, W is the energy stored in the cavity, δ is the single-pass energy loss rate in the cavity; n is the refractive index of the acousto-optic crystal medium, c is the speed of light, L is the geometric length of the cavity and λ_0 is the laser wavelength in a vacuum.

From Equation (5), it can be seen that when the single-pass energy loss rate in the cavity and the length of the laser cavity are fixed, the quality factor Q is inversely proportional to the losses of the optical resonator. This means that when the optical resonator losses are higher, the Q value is lower, the threshold is higher, and laser oscillation is harder to achieve. Conversely, when the losses are lower, the Q value is higher, the threshold is lower, and the laser is more likely to oscillate. Therefore, the threshold of the laser can be adjusted by changing the Q value of the optical resonator.

The pulse width of a Q-switched laser can be calculated using the following formula [18]:

$$t_p = \frac{2L}{c\left(\ln\left(\frac{1}{R_{oc}}\right) + L_{oss}\right)} \left[\frac{n_i - n_f}{n_i - n_t\left(1 + \ln\left(\frac{n_i}{n_t}\right)\right)} \right] \tag{6}$$

where L is the total cavity length, R_{oc} is the reflectivity of the output coupling mirror, c is the speed of light, L_{oss} is the cavity loss, n_i is the initial inversion particle density, n_f is the final inversion particle density, and $n_t = \left[\ln\left(\frac{1}{R_{oc}}\right) + L_{oss}\right] / 2\sigma L_{cry}$ is the threshold inversion particle density. Here, σ is the stimulated emission cross-section at 1064 nm, and L_{cry} is the length of the Nd:YAG crystal rod. As can be seen from the above formula, the simplest and most effective method to achieve long nanosecond pulse lasers is to extend the length of the laser resonator. The characteristics of the 4f resonator ensure that the laser q-parameter remains unchanged with the extended-cavity length, thereby ensuring the stability and efficiency of the output laser.

3. Experimental Setup

The device diagram of the 532 nm acousto-optic Q-switched laser is shown in Figure 2. The laser head is an Nd:YAG module pumped by a LD, with Nd^{3+} ion doping concentration of 0.6 at%, and the crystal dimensions are Φ4 × 100 mm. The structure of LD pump is a 5-way ring pump, with 5 bars in each direction and a maximum power of 40 W per bar. The end faces of the laser crystal are coated with an anti-reflection film for 1064 nm to reduce Fresnel reflection. To ensure temperature stability of the Nd:YAG crystal, the laser pumping module uses a 5.2 kW water chiller for cooling, with the cooling water temperature set to 25 °C. An acousto-optic Q-switch (QS27-5C4G-U5-ST1) manufactured by GOOCH & HOUSEGO (Ilminster, UK) is used. The working medium is molten silicon, and the crystal surface is coated with multiple layers of dielectric hard film. This film not only increases the transmittance at 1064 nm to over 99.6%, but also raises the damage threshold (>1 GW/cm^2), effectively protecting the crystal from high-power laser damage. Additionally, this design ensures that the insertion loss remains at a low level (<6%), which is crucial for achieving high-power pulsed lasers. The device's overheat protection mechanism is also noteworthy, with a protection threshold set at 55 °C, ensuring stable operation within a safe temperature range. Two acousto-optic Q-switches are placed perpendicularly on either side of the Nd:YAG laser module. This arrangement ensures precise matching of the acoustic and oscillation beam apertures and effectively achieves precise laser shutdown under high-power conditions by enhancing the acousto-optic diffraction capability. To ensure signal synchronization between the two acousto-optic Q-switches, they are driven by the same acousto-optic driver, which is crucial for stable laser output.

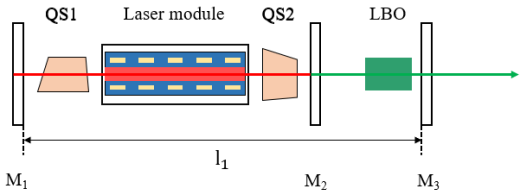


Figure 2. Schematic diagram of a 532 nm acousto-optic Q-switched laser with a cavity length of 600 mm.

The LBO frequency doubling crystal has dimensions of $4 \times 4 \times 16$ mm^3. To improve the frequency doubling efficiency, the LBO crystal is placed close to the M_3 position. To optimize the temperature control of the crystal, the LBO crystal is placed in a copper heat sink with a water-cooling channel and wrapped with indium foil to ensure comprehensive contact between the crystal and the heat sink for effective heat dissipation. A thermistor is installed at one end of the heat sink near the crystal to monitor the temperature in real time. The LBO crystal is precisely temperature-controlled by a Thermo Electric Cooler (TEC), with temperature fluctuations maintained within ± 0.1 °C, which effectively enhances the frequency doubling efficiency and stability of the laser. After a series of tests, it was found that the laser output power reaches its peak at a crystal temperature of 27 °C, so the TEC temperature is set to 27 °C. During the experiment, the angle and position of the LBO crystal are continuously adjusted to achieve optimal phase matching and maximize laser output. The mirror M_1 is a plane mirror with a surface coating of high-reflectivity film for 1064 nm (R > 99.5%@1064 nm). The mirror M_3 is a plane output mirror, with high-transmission coatings for 532 nm and high-reflectivity coatings for 1064 nm on both surfaces (T > 99%@532 nm, R > 99.5%@1064 nm). The mirror M_2 is a plane dichroic mirror with a high-reflectivity coating for 532 nm and a high-transmission coating for 1064 nm on the surface near the LBO crystal (R > 99.5%@532 nm, T > 95%@1064 nm), and the other surface is coated with an anti-reflection film for 1064 nm. The function of M_2 is to allow the fundamental frequency light to pass through the frequency doubling crystal twice, effectively improving the frequency doubling efficiency. And a sub-cavity for frequency doubling is formed between M_2 and M_3. Mirror M_3 is placed symmetrically with respect to the crystal rod, with a distance l_1 of 600 mm from mirror M_1.

The experimental setup of the long-pulse-width 532 nm acousto-optic Q-switched laser is shown in Figure 3. By moving mirror M_1 further from the laser cavity, the cavity is extended, doubling the total length. A pair of spherical lenses is added to the extended cavity to show the previous positions of the mirrors compared to the new positions. Thus, despite the significantly longer and highly asymmetric cavity, its performance resembles that of a shorter cavity with stable laser characteristics and consistent stability parameters over the entire pump power range. The lenses L_1 and L_2, with a focal length of f = 150 mm, form a 4f optical system. The distance between the output mirror M_3 and the virtual position M_1' is l_1 = 600 mm, and the distance between the virtual position and the back mirror M_1 is l_2 = 600 mm. The distance between lenses L_1 and L_2 is twice the focal length of the lenses, i.e., 300 mm.

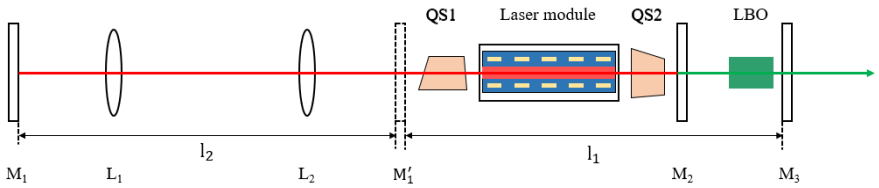


Figure 3. Schematic diagram of a long-pulse-width 532 nm acousto-optic Q-switched laser.

4. Results and Discussion

Figure 4 shows the relationship between the average power of the 532 nm laser and the pump current when the repetition rate is 10 kHz. The red curve represents the output

power of the 532 nm laser with the 4f optical system, i.e., the extended cavity, while the black curve represents the output power of the 532 nm laser with the short cavity. From Figure 4, it can be observed that as the pump current increases, the average power of the 532 nm laser also increases. However, when the pump current reaches between 16 and 19 A, the rate of increase in average power significantly slows down. This change is due to the thermal effects of the Nd:YAG crystal impacting the stability of the resonator, causing the laser to enter an unstable operating region. As the pump current continues to increase, the laser returns to a stable operating region, allowing the average power of the 532 nm laser to continue growing. Ultimately, at a pump current of 28 A, the output power of the 532 nm laser with the short cavity reaches a maximum of 127 W, while the output power of the 532 nm laser with the 4f optical system reaches a maximum of 112 W. Additionally, it can be observed that with the addition of the 4f optical system, the doubling of the laser cavity length leads to a decrease in laser power. The primary reason for the decrease in power is that the coating on the convex lens is not a 100% anti-reflective coating, which results in losses due to partial reflections from the two convex lens surfaces and absorption by the lens.

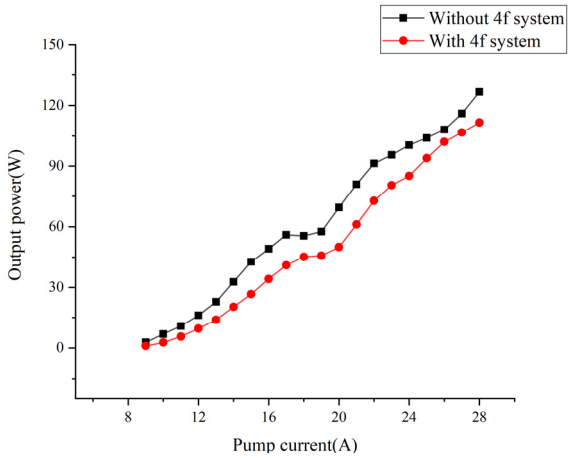


Figure 4. The output power of the short-cavity 532 nm laser and the 4f extended-cavity laser under different pump currents.

The experiment used a photodetector (THORLABS, DET10A2) (Newton, NJ, USA) and an oscilloscope (Tektronix, TDS3054B) (Beaverton, OR, USA) to measure the pulse width. Figure 5 shows the relationship between the pulse width of the 532 nm laser and the pump current. The red curve represents the pulse width variation of the 532 nm laser with the 4f optical system, i.e., the extended cavity, while the black curve represents the pulse width variation of the 532 nm laser with the short cavity. From the figure, it is clear that the pulse width decreases as the pump current increases. When the pump current is 28 A, the pulse width of the short-cavity laser reaches 58 ns, while the pulse width of the 4f optical system extended-cavity laser reaches 85 ns. The pulse width broadening ratio is 46.5%, indicating a significant increase in pulse width. From Figure 5, it can be seen that the pulse width gradually decreases because, with increasing current, the gain gradually increases, leading to more particles reversing per unit time and thus a narrower pulse width for Q-switching. Additionally, losses within the laser cavity contribute to a reduced rate of pulse width broadening.

The time series of the short-cavity 532 nm laser and 4f extended-cavity laser reveal the dynamic behavior of the laser under different pump currents, including periodicity, quasi periodicity, and possible chaotic roaming phenomena. The evolution path of the laser state in phase space indicates that the system may evolve into a chaotic attractor under specific pump currents [19]. This evolutionary process is consistent with known chaotic scenarios, such as period doubling and quasi periodic paths, indicating that pump current is a key parameter controlling the chaotic behavior of lasers. As the pump current increases,

the laser transitions from a stable laser output to a chaotic state. This transition can be observed through time series analysis, where periodic patterns are gradually replaced by more complex dynamics [20].

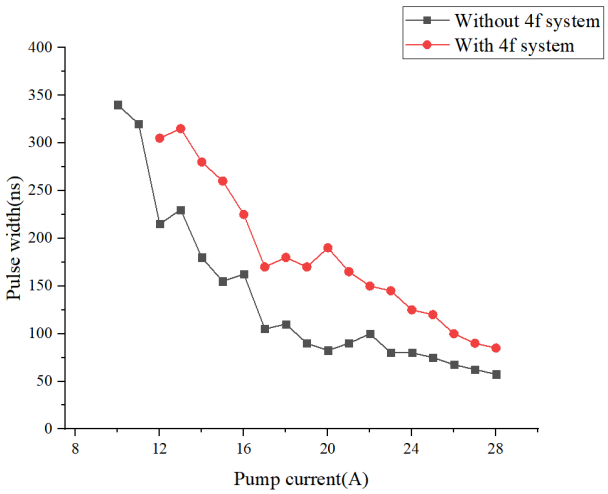


Figure 5. The pulse width of the short-cavity 532 nm laser and the 4f extended-cavity laser under different pump currents.

M^2 is used to evaluate beam quality, which is defined as the ratio of the product of beam parameters to the product of beam parameters of the fundamental mode Gaussian beam:

$$M^2 = \frac{\pi D_o \theta}{4\lambda} \quad (7)$$

In the formula, D_0 is the waist width, θ is the beam divergence angle, and λ is the wavelength of the laser. Using the beam quality analyzer (M2DU-200 Stage) (Redding, CA, USA) from DataRay, when the short-cavity 532 nm laser outputs 110 W, its beam profile and quality are shown in Figure 6. The blue and red curves represent the beam quality in the X and Y directions, respectively. The beam quality factors are M_x^2 = 12.62 in the horizontal direction and M_y^2 = 14.67 in the vertical direction. For the 532 nm laser with the 4f optical system extended cavity, with an output power of 108 W, the beam profile and quality are shown in Figure 7. The laser beam is nearly circular with a typical Gaussian intensity distribution. At 108 W output power, the beam quality factors are M_x^2 = 15.76 in the horizontal direction and M_y^2 = 14.25 in the vertical direction. The decline in beam quality for the 532 nm laser is attributed to aberrations introduced by the two spherical mirrors and the misalignment of the image plane (M_1').

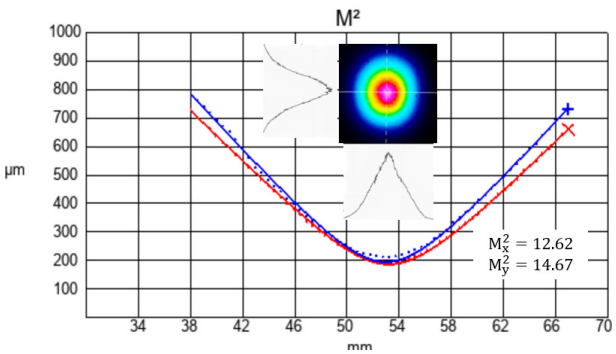


Figure 6. The beam profile and beam quality of the short-cavity 532 nm laser at 110 W power (The blue and red curves represent the beam quality in the X and Y directions, respectively).

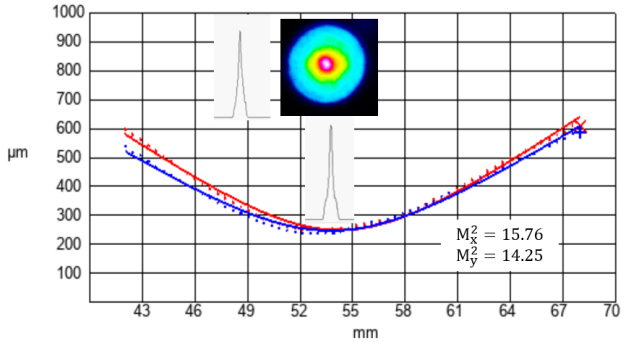


Figure 7. The beam profile and beam quality of the 532 nm laser with the 4f optical system at 108 W power (The blue and red curves represent the beam quality in the X and Y directions, respectively).

5. Conclusions

Based on a high-power 532 nm laser with frequency doubling in a dual acousto-optic Q-switch cavity, this paper sets out a design for a high-power long-pulse-width 532 nm laser. By using a 4f optical system, it achieves image transfer properties, ensuring that the q-factor remains constant within the laser cavity, thus allowing for an extended-cavity length and longer pulse width. During the experiment, under a 10 kHz repetition frequency condition, there was no significant decrease in the average power compared to the short-cavity power, with a maximum output power of up to 112 W achieved. Due to reflection losses and lens absorption, the power conversion efficiency was 88.2%. A pulse width of 85 ns was also achieved, with a pulse width broadening rate of 45.6% due to losses. The beam quality slightly degraded due to aberrations and misalignment, but the shape remained relatively good.

Author Contributions: Conceptualization, X.L.; methodology, X.L.; software, J.H.; validation, J.H. and H.L.; formal analysis, W.L.; investigation, J.H.; resources, H.L.; data curation, N.X.; writing—original draft preparation, J.H.; writing—review and editing, J.H.; visualization, Y.L. and T.Z.; supervision, D.L. and Z.W.; project administration, X.L.; funding acquisition, X.L. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: Author Dong Li was employed by the company AVIC Beijing Aeronautical Manufacturing Technology Research Institute. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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