5.32 mJ and 47.5 kW cavity-dumped Pr:YLF pulsed laser at 639 nm

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Abstract
In this work, we confirm a Pr:YLF pulsed laser with high power and high energy at 639 nm based on the acousto-optic cavity dumping technique. The maximum average output power, narrowest pulse width, highest pulse energy, and peak power of the pulsed laser at a repetition rate of 0.1 kHz are 532 mW, 112 ns, 5.32 mJ, and 47.5 kW, respectively, the 639 nm pulsed laser with such high pulse energy and peak power have never been reported so far. Furthermore, we obtain a widely tunable range of repetition rates from 0.1 kHz to 5000 kHz. The diffracted beam quality factors M^2 are 2.18 (in x direction), and 2.04 (in y direction), respectively. To the best of our knowledge, it is the first time that a cavity-dumped all-solid-state pulsed laser in visible band is reported so far. This work provides a promising method for obtaining high-performance pulsed lasers.

Keywords: 639 nm, Pr:YLF, cavity dumping technique, pulsed laser

1. Introduction

Visible lasers have important applications in biomedical, industrial processing, communications and military fields [1-5]. There have been numerous reports on

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continuous-wave (CW) visible lasers based on Pr:YLF crystals [6-9], compared to green laser, orange laser and other band, the laser at 639 nm has the highest emission cross section of ~22.3×10^{-20} cm^2 [10-11], which implies that the highest output power may be obtained at wavelength of 639 nm on Pr:YLF. To the best of our knowledge, the highest output power of CW laser reported at 639 nm is 8.14 W [12], however, this output power is not sufficient for some specific applications, e.g. metal cutting. Pulsed lasers are becoming a hot spot for research because of its potential of high power and high energy.

Several studies have been reported on 639 nm Pr:YLF pulsed lasers, the methods used in reports mainly include active Q-switching and passive Q-switching. In 2014, based on a Pr:YLF crystal, Kojou et al. use an acousto-optic modulator (AOM) as a modulating switch to obtain 320 nm and 261 nm pulsed lasers by intracavity frequency doubling in the experiment, the pulse width, pulse energy, and peak power of the 640 nm pulsed laser at a repetition rate of 7.7 kHz are obtained as 17 ns, 27 μJ, and 1,57 kW, respectively [13]. In 2020, Jin et al. use the method of Q-switching pre-lase in conjunction with Fabry–Perot etalon to obtain a single-longitudinal-mode 639 nm Pr:YLF pulsed laser directly, the pulse width, peak power, and single pulse energy at repetition rate of 10 kHz are 81.1 ns, 48.5 W, and 3.94 μJ, respectively [14]. In 2022, Under the pumping of blue LD, Yang et al. obtain Pr:YLF high-energy pulsed laser at 639 nm for the first time by electro-optic Q-switching, the highest pulse energy, peak power, pulse width and average power are 260 μJ, 1898 W, 137 ns, and ~26 mW, respectively, the tunable range of repetition rate is from 100 Hz to 500 Hz, the pulse energy and peak power are the highest values at that time [15]. In 2024, under the pumping of a 24 W blue light pump source, Xue et al, obtain the 639 nm Pr:YLF pulsed laser with watt-level average power for the first time, an AOM is used as Q-switcher, the pulse width, average output power, pulse energy, and peak power are 40 ns, 1.136 W, 110 μJ and 2.796 kW, respectively [16]. In 2021, Badtke et al. present passive Q-switching at 640 nm using Co:$MgAl_2O_4$ as a saturable absorber, with a narrowest pulse width of 8.5 ns at a repetition rate of 0.78 MHz. However, the average output power, pulse energy, and peak power are not so good, corresponding values are 1 W, 1.3 μJ, and 140 W, respectively [17]. From the works reported above, it is easy to see that the pulse energy and peak power of the 639 nm laser are still relatively low, the tunable range of repetition rate is narrow, and a stable 639 nm pulsed laser at high repetition rate is not realized.

As far as we know, pulsed lasers based on cavity dumping technique are mainly focused on the near-infrared band, for example: 1989.8 nm [18], 2013 nm [19], 2012.6 nm [20], the gain mediums are mainly Tm:YAP, Tm:YAG, and Nd:$GdVO_4$, etc., and the cavity-dumped pulsed lasers based on Pr:YLF crystals have not been reported yet.

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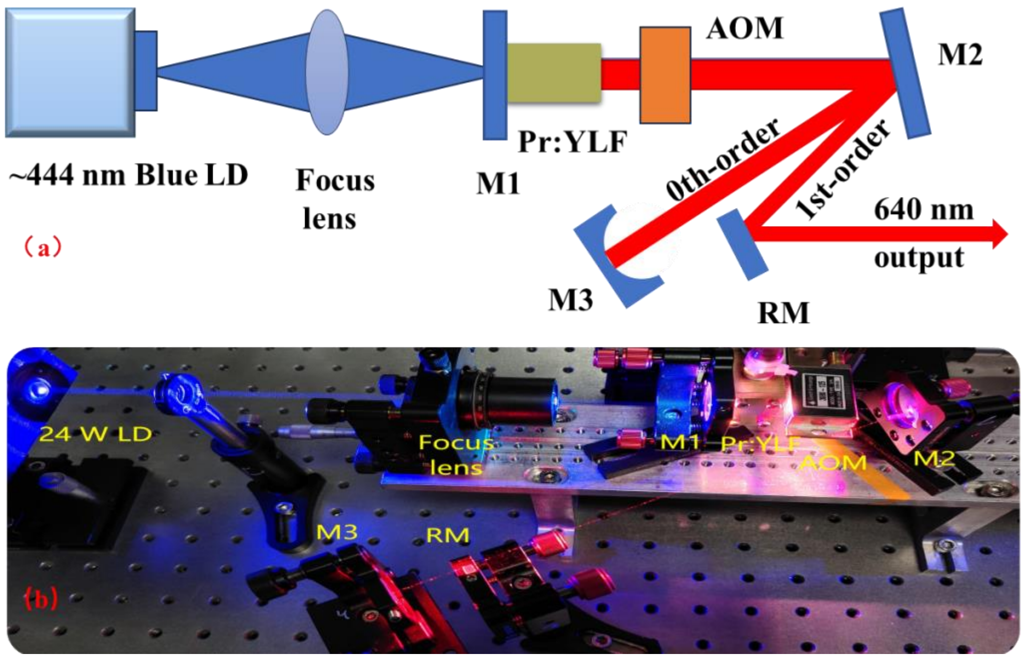

Figure 1. (a) Schematic diagram of experimental setup, (b) Physical diagram of experimental setup.

In this work, we use an AOM as a modulating switch, and a Pr:YLF crystal as a gain medium. The 1st-order diffracted laser separated from the AOM is reflected out of the resonant cavity as the output laser. We obtain a pulsed laser with a widely tunable repetition rate range from 0.1 kHz to 5000 kHz, and the average output power, pulse width, pulse energy, and peak power of the 639 nm pulsed laser are 532 mW, 112 ns, 5.32 mJ, and 47.5 kW at a repetition rate of 0.1 kHz, respectively, an order of magnitude increase in pulse energy and peak power of 639 nm pulsed laser is achieved. As a result, a 639 nm high-performance pulsed laser based on acousto-optic cavity dumping technique is obtained.

2. Experimental setup

As shown in Figure 1, the coupled mirrors of M1, M2 and M3 are used to form a V-shaped resonant cavity. A commercial 24 W blue LD is used as pump source, which has a vertically polarized continuous light with a central wavelength of 444 nm. The pump light is focused into the crystal by the focusing of a 75 mm plano-convex focus lens, and waist radius of the pump light is measured to be ~123 μm. M1 and M2 are plane mirrors with high transmittance at 444 nm, the transmittance is 98.14% and 91.49%, respectively, they have high reflectivity to red light at 639 nm, the transmittance is almost 0. M3 is a concave mirror with a radius of curvature of 300 mm, which is highly reflective of red light at 639 nm (transmittance of ~0.39%). The transmittance curves of the three coupled mirrors are shown in Figure 2. AOM (model number:3080-125) is an acousto-optic modulator for the switching control of laser at 639 nm from Grooch & Housego, which have the tunable wavelength range of 450 nm-850 nm, the active aperture of 2.5 mm (L) × 2.0 mm (H), the rise/fall time of 25 ns, the center frequency of 80 MHz, and the RF bandwidth of 25 MHz @-9dB return loss. Under the modulating of AOM, the diffracted

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lasers of 0th-order and 1st-order are generated. RM is a plane mirror with high reflectivity at 639 nm and high transmittance at 444 nm, which is used to reflect 1st-order diffracted laser outside the resonant cavity. The gain medium used in the experiments is an a-cut Pr:YLF crystal with length of 14 mm, which has a doped concentration of 0.15 at%, the size of polished facets are 3×3 mm^2. The crystal is wrapped in indium foil, and placed inside a copper block, with its π direction parallel to the vertical direction, which cooled by a water-cooling system set at 10 ℃. As a result, we successfully obtain a cavity-dumped pulsed laser by optimizing the resonant cavity and adjusting the angle of the AOM.

We calculate the waist radius of the laser in the crystal and laser size (close to the crystal) at the end face of AOM, which are approximately 41 μm and 42.7 μm, respectively.

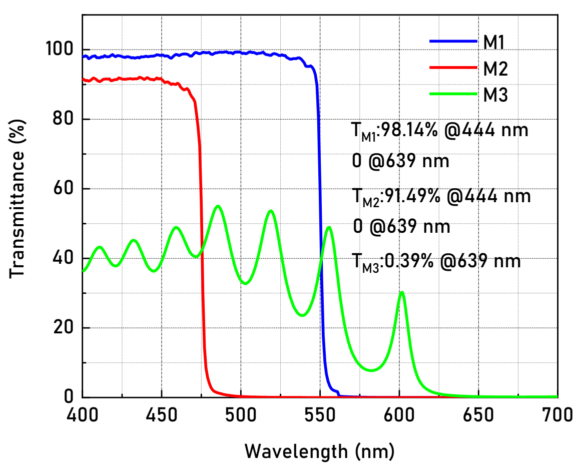

Figure 2. Optical transmittance properties of M1, M2 and M3.

3. Results and discussion

In the experiment, the power absorption efficiency of Pr:YLF crystal is about 43%, we find that the output power saturate with the increase of pump power, and the maximum absorbed pump power of the crystal is about 7.3 W. In order to protect the crystal from damage, we do not continue to increase the pump power. In our opinion, the short length of the crystal and the shift in the central wavelength of the pump source at high power are the main reasons for the unsatisfactory absorption efficiency.

As shown in Figure 3, Under the pumping of maximum absorbed pump power, we measure the average output power of the 1st-order diffracted laser at different repetition rates. At a repetition rate of 0.1 kHz, we obtain a pulsed laser with maximum average output power of 532 mW, and the maximum average output power is 453 mW at a repetition rate of 5000 kHz. It can be seen that the average output power shows an overall decreasing trend. In our view, this is related to the evolution of population inversion density and photon density in cavity. The lifetime of the upper energy level ($^3P_0$) at wavelength of 639 nm based on Pr:YLF crystal is approximately 50 μs [21-23], when the pulse interval of pulsed laser is less than 50 μs (repetition rate > 20 kHz), this will result in insufficient accumulation of inverted population in the upper energy level. As the repetition rate increases, the population inversion density accumulated in the upper energy level decreases, and the average output power decreases.

Inset shows the absorbed pump power versus the average output power at repetition rates of 0.1 kHz and 5000 kHz. It is not difficult to see that as the absorbed pump power increases, the average output power shows an increasing trend. When the absorbed pump power is greater than 7 W, the average output power shows significant saturation.

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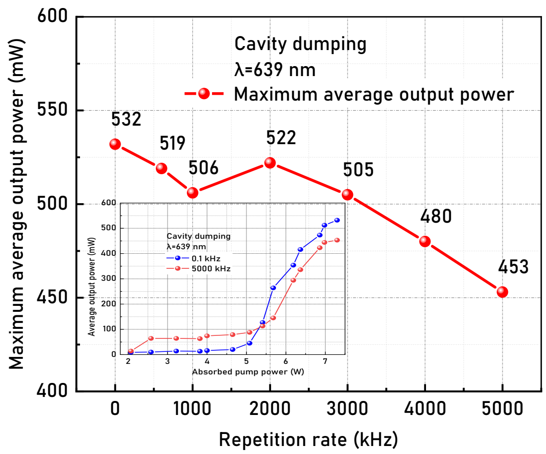

Figure 3. Maximum average output power at different repetition rates (0.1 kHz, 600 kHz, 1000 kHz, 2000 kHz, 3000 kHz, 4000 kHz, and 5000 kHz). Inset is average output power versus absorbed pump power at repetition rates of 0.1 kHz and 5000 kHz.

When coating the film for M3, even though we set the transmittance to zero at wavelength of 639 nm, the ideal fully reflective mirrors is difficult to obtain. As we present in Figure 2, the real transmittance of M3 at 639 nm is 0.39%. According to the principle of obtaining pulsed lasers by cavity dumping technique, this will reduce the output power of 1st-order diffracted laser. We believe that replacing M3 with a fully reflective mirror at 639 nm will improve the output power of 1st-order diffracted light.

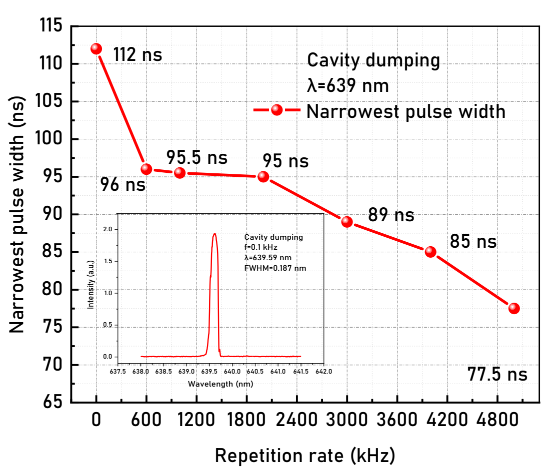

Figure 4. Narrowest pulse width at different repetition rates (0.1 kHz, 600 kHz, 1000 kHz, 2000 kHz, 3000 kHz, 4000 kHz, and 5000 kHz). Insert is the spectrum at 0.1 kHz.

At the maximum absorbed pump power, we record the narrowest pulse widths at different repetition rates, as shown in Figure 4. the narrowest pulse width at repetition rate of 0.1 kHz and 5000 kHz are 112 ns and 77.5 ns, separately. As the repetition rate increases, the narrowest pulse width slightly decreases. We believe that the probable cause of the decreasing trend in pulse width is due to the non-standard output of square wave pulses from the signal source. The pulse width of cavity-dumped pulsed laser is mainly related to the length of resonant cavity and the switching speed of AOM, the real length of resonant cavity is approximately 270 mm, and the rising or falling edge time of AOM is 25 ns. We believe that shortening the length of the resonant cavity and replacing AOM with shorter rising or falling edge times are beneficial for obtaining narrower pulse width of pulsed laser. The inset shows the spectrum at a repetition rate of 0.1 kHz, with central wavelength of 639.59 nm and the full width at half maximum (FWHM) of 0.187 nm. We measure the spectrum by Advantest Q8341.

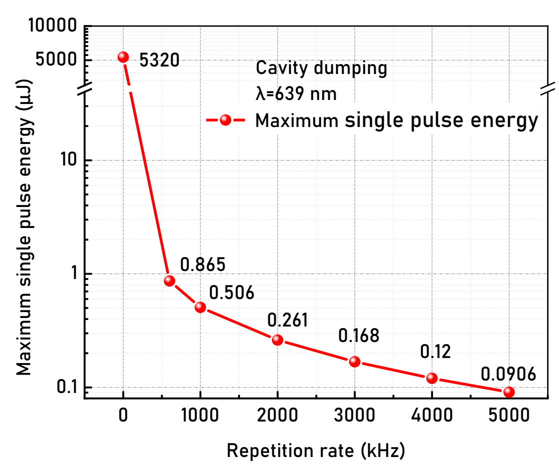

Figure 5. Maximum single pulse energy at different repetition rates (0.1 kHz, 600 kHz, 1000 kHz, 2000 kHz, 3000 kHz, 4000 kHz, and 5000 kHz).

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According to the equations for pulse energy and peak power: $E=P/f$ and $P_{peak}=E/\tau$ [24], where E, P, f, P_{peak} and τ are single pulse energy, average output power, repetition rate, peak power, and pulse width, respectively. Figure 5 shows the curve of maximum pulse energy at different repetition rates. As we can see, the maximum single pulse energy of 5320 μJ at a repetition rate of 0.1 kHz, which, to the best of our knowledge, is the maximum single pulse energy at 639 nm reported so far. As the

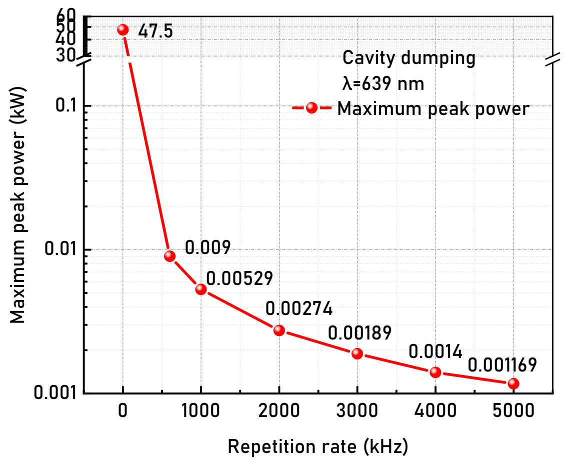

Figure 6. Maximum peak power at different repetition rates (0.1 kHz, 600 kHz, 1000 kHz, 2000 kHz, 3000 kHz, 4000 kHz, and 5000 kHz).

repetition rate increases, the maximum single pulse energy decreases rapidly. In our opinion, the increase in repetition rate leads to an increase in the number of pulses per unit time in cavity dumping operation, while the average output power does not increase, which results in a smaller single pulse energy. As show in Figure 6, we achieve the maximum peak power of 47.5 kW at repetition rate of 0.1 kHz. As far as we know, this is the first time that a 639 nm pulsed laser with such high peak power is obtained. The pulse energy and peak power of pulsed laser at 639 nm have been greatly improved in this work.

Figure 7 demonstrates the spectral characteristics of the 639 nm pulsed laser at a repetition rate of 0.1 kHz, we can see that the spectrum with the pulse width of 112 ns overlaps well with the curve by Gaussian fitting, which proves the formation of a Gaussian-like laser. The inset is the pulse train recorded by the oscilloscope, and the fluctuation of pulse train is ~1%.

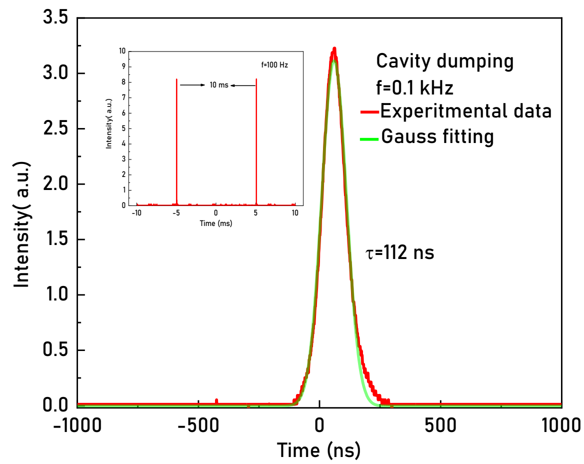

Figure 7. Single pulse and typical pulse train (insert) at repetition rates of 0.1 kHz.

Figure 8 shows the pulse trains of the 639 nm pulsed laser at different repetition rates of 600 kHz, 1000 kHz, 2000 kHz, 3000 kHz, 4000 kHz, and 5000 kHz. We can see that cavity-dumped lasers have advantage with a wide range of tunable repetition rates (from 0.1kHz to 5000kHz in this work) over Q-switched pulsed lasers, the highest tunable repetition rates of Q-switched pulsed lasers are generally in the tens or hundreds of kHz [16,25,26]. It is not difficult to see that within the range of tunable repetition rates, the pulse trains of the

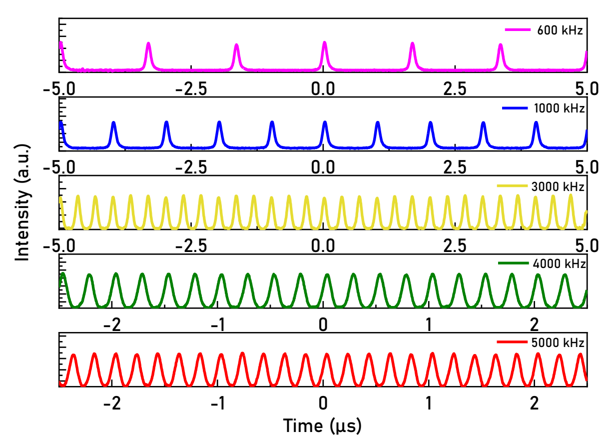

Figure 8. Typical pulse trains at different repetition

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rates (600 kHz, 1000 kHz, 3000 kHz, 4000 kHz, and 5000 kHz).

pulsed laser are very stable. What's more, this work provides a very promising method for obtaining pulsed lasers with high repetition rate. In this experiment, in order to ensure the time conditions of accumulation of inverted population and photon oscillation in cavity at different repetition rates, we adjust slightly the duty cycle of the pulse signal input by the signal generator.

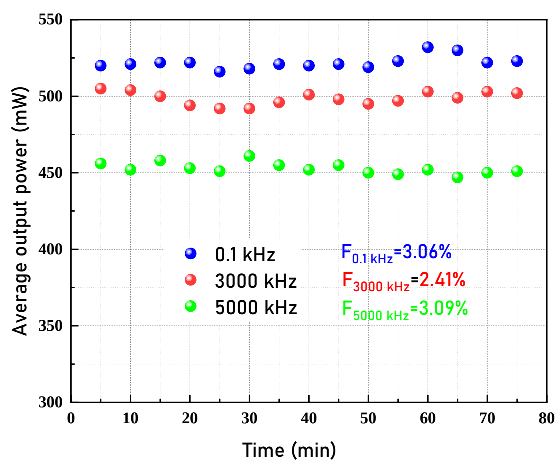

Figure 9. Stability of maximum average output power at different repetition rates (0.1 kHz, 3000 kHz, and 5000 kHz).

Under the maximum absorbed pump power, the stabilities of maximum average output power are recorded at different repetition rates. As shown in Figure 9, the power fluctuations at different repetition rates of 0.1 kHz, 3000 kHz, and 5000 kHz are 3.06%, 2.41%, and 3.09%, respectively. We believe that the stability of the pump source is the key to the stability of maximum average output power. Based on our experimental experience, the unstable diffraction of AOM is also one of the factors affecting the stability of the maximum average output power. In addition, the thermal lensing effect of crystal can lead to instability of output power.

Figure 10 demonstrates laser beam quality of the cavity-dumped pulsed laser. At the maximum output power, the beam quality factors M^2 are 2.18 (in x direction) and 2.04 (in y direction) at repetition rate of 0.1 kHz, respectively. The inset shows the beam profile captured by a CCD camera, this reconfirms that the pulsed laser is a Gaussian-like laser.

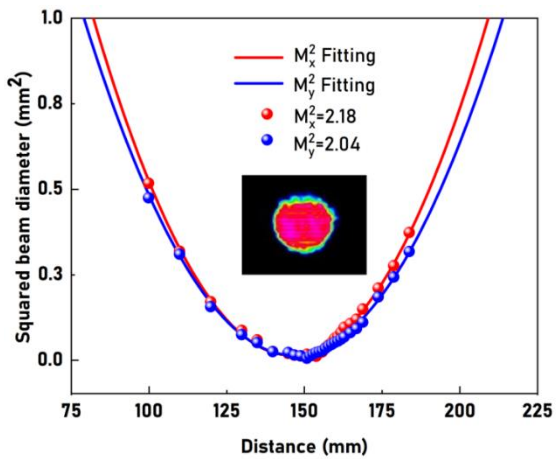

Figure 10. Beam quality M^2 factors of cavity-dumped laser at 639 nm and beam profile captured by CCD camera.

During the experiment, the thermal lensing effect of the crystal inevitably affects the beam quality. We think that lowering the temperature of cooling system would improve the beam quality of the pulsed laser. However, since the temperature of laboratory could not be lowered any further, this difference of temperature with copper block and air in the laboratory would lead to the condensation of water droplets on the surface of the copper block, which is a serious threat to the safety of the Pr:YLF crystal. Therefore, we maintain the temperature of cooling system at 10℃. In addition, the stability of the pump source also affects the beam quality of the pulsed laser.

In order to visually compare the performance of 639 nm pulsed lasers, we list several representative reports in Table 1. It is easy to see that the cavity-dumped pulsed laser has significant advantage in laser performance.

Table 1. Performance comparison of pulsed laser at 639 nm

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Operation Regime	Average power (mW)	Pulse width (ns)	Pulse energy (μJ)	Peak power (kW)	Repetition rate (kHz)	Refs
AO-switching	-	17	27	1.57	7.7	13
AO-switching	-	81.1	3.94	0.0485	10	14
EO-switching	26	137-418	260	1.898	0.1-0.5	15
AO-switching	1136	40-270	110	2.796	10-50	16
Co:MALO	1000	8.5-30	1.3	140	~40-840	17
Cavity-dumping	532	77.5-112	**5320**	**47.5**	**0.1-5000**	This work

The cavity-dumped pulsed laser has the highest pulse energy and peak power at 639 nm. Moreover, the widest range of tunable repetition rates (0.1 kHz to 5000 kHz), which can meet the needs of pulsed lasers with high repetition rate in some specific applications, such as, pulsed laser source with high repetition rate.

4. Conclusion

In summary, we confirm a high-performance cavity-dumped 639 nm all-solid-state pulsed laser based on an Pr:YLF crystal. At repetition rate of 0.1 kHz, the maximum average output power, narrowest pulse width, highest pulse energy, and hightest peak power are 532 mW, 112 ns, 5.32 mJ, and 47.5 kW, respectively, the fluctuation of average output power is 3.06%, and the 1st-order diffracted beam quality factors M^2 are 2.18 (in x direction) and 2.04 (in y direction), respectively. An order-of-magnitude improvement in pulse energy and peak power of 639 nm pulsed laser is achieved compared to the results of previous reports. In addition, the widest range of tunable repetition rate for the pulsed laser is obtained (0.1 kHz to 5000 kHz). To the best of our knowledge, this is the first demonstration of cavity-dumped solid-state pulsed laser in the visible band, this work provides a highly potential approach for obtaining high-performance pulsed lasers. In future work, we believe that the performance of pulsed laser can be further improved by shortening the length of the resonant cavity, and replacing the Pr:YLF crystal with a longer one. In addition, replacing the output of 1st-order diffracted laser with 0th-order diffracted laser may also improve the performance of laser.

Acknowledgments

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