

Quasi-three-level Nd:GdYNbO₄ 927 nm laser under 879 nm laser diode pumping

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Abstract

We report an 879 nm laser diode (LD) end-pumped quasi-three-level 927 nm laser with a Nd:GdYNbO₄ mixed crystal for the first time to the best of our knowledge. Comparing the 927 nm laser's performance under 808 nm and 879 nm LD pumping, we find performance enhancement is achieved by using direct 879 nm LD pumping. A maximum output energy of 42 mJ at 10 Hz is obtained in the 879 nm LD pumped 927 nm laser with an optical-to-optical efficiency of 24% and a beam quality factor of $M^2 = 1.7$. The dependence of output characteristics on the pumping repetition rate is discussed. The average output power at 927 nm reaches 1.13 W at 100 Hz with an optical-to-optical efficiency of 6.5%.

Keywords: laser diode (LD) pumped, quasi-three-level, direct pumping, Nd:GdYNbO₄

1. Introduction

Diode-pumped solid-state lasers have the advantages of compactness, high efficiency and low cost. Great efforts have been made to investigate laser performance with different gain materials under laser diode (LD) pumping [1–3]. Neodymium (Nd³⁺)-doped crystals are efficient gain media to generate laser around 1.06 μm via the laser transition ($4F_{3/2} \rightarrow 4I_{11/2}$), which are widely used in industrial, medical and military applications [4, 5]. Other transitions in Nd³⁺-doped crystals are also intensively studied to produce lasers at wavelengths of 0.9 μm , 1.3 μm and 1.8 μm . Lasers at shorter wavelength around 0.9 μm could be utilized as laser sources for different absorption lidar for water vapor detection. Moreover, by frequency doubling blue lasers could be generated with many applications ranging from underwater communication, color displays, and biological diagnostics to optical data storage [6–8]. Since Fan and Byer demonstrated the first end-pumped Nd:YAG 946 nm laser in 1989 [9], plentiful investigations have been conducted on Nd³⁺-doped quasi-three-level lasers with different host materials [10–16]. Mixed laser materials have broadened fluorescence spectra and long lifetimes. During the past decade, various Nd³⁺-doped mixed laser crystals have been developed and investigated such as Nd:LuGdVO₄ [17], Nd:GaYAlO₄ [18], Nd:LuYAG [19], and Nd:GdYTaO₄ [20]. Due to similar ionic radii, Y³⁺ and Gd³⁺ ions are usually employed to generate mixed laser materials. In 2015, Dou *et al* presented a novel Nd:GdNbO₄ crystal grown by the Czochralski (Cz) method and obtained an efficient 1066 nm laser via the $4F_{3/2} \rightarrow 4I_{11/2}$ transition [21]. In 2017, Ding *et al* demonstrated a mixed crystal Nd:GdYNbO₄ by the Cz method and obtained an LD-pumped Nd:GdYNbO₄ 1066 nm laser with an output power of 0.98 W and an optical-to-optical efficiency of 30.4% [22]. The absorption cross section for Nd:GdYNbO₄ at ~ 808 nm is 11.6×10^{-20} cm² with a bandwidth of 5–14 nm while its fluorescence lifetime of 156 μs is beneficial for energy storage [22]. Direct pumping to the upper laser level of the Nd³⁺ ion is an effective approach to reduce losses induced by the Stokes factor and increase laser efficiency [23–25]. Recently direct pumping has been widely used in Nd³⁺-doped lasers with the development of LD around 880 nm [26–29].

In this paper, we report an 879 nm LD end-pumped quasithree-level 927 nm laser with a Nd:GdYNbO₄ mixed crystal for the first time to the best of our knowledge. The fluorescence spectrum of the Nd:GdYNbO₄ crystal around 920 nm is investigated. The 927 nm laser's performances under 808 nm and 879 nm LD pumping are compared in the same conditions. The output energy at 927 nm reaches 24.0 mJ under 808 nm LD pumping, corresponding to a slope efficiency of 31.0% and an optical-to-optical efficiency of 19.0%. In comparison, the slope efficiency of the 879 nm LD pumped 927 nm laser is enhanced to 42.5%. A maximum output pulse energy of 42 mJ at 927 nm is achieved at 10 Hz with an optical-to-optical efficiency of 24%. The output characteristic of the LD-pumped 927 nm laser at different repetition rates is investigated. The maximum average output power reaches 1.13 W at 927 nm when the pumping repetition rate is 100 Hz.

2. Experimental setup

Nd:GdYNbO₄ crystal is grown by using the Cz method. The raw materials of Gd₂O₃, Y₂O₃, Nb₂O₅, and Nd₂O₃ compounds are weighted according to the chemical formula Nd_{0.01}Gd_{0.69}Y_{0.3}NbO₄. A c-cut Nd:GdYNbO₄ crystal is used as the laser medium with a Nd³⁺ doping concentration of 1 at% and dimensions of 2(W) × 2(H) × 4(L) mm³. Figure 1 shows the experimental setup of the LD end-pumped Nd:GdYNbO₄ quasi-three-level 927 nm laser. A high-brightness fiber-coupled 879 nm LD serves as pump source with a fiber diameter of 400 μm and an NA of 0.22. By using a volume Bragg grating (VBG), the wavelength of the LD is stabilized at 878.6 nm with a spectrum width of 0.6 nm. The LD works in quasi-continuous-wave operation with a duty cycle of 2% and a repetition rate of 10 Hz to reduce the influence of thermal effects on laser performance. The pump beam is re-imaged into the gain medium by using a pair of aspherical lenses. The laser crystal is wrapped with a 0.05 mm thick indium foil, mounted in a micro-channel heat sink and kept at 18 °C by water cooling. Both facets of the laser rod are coated with high transmission (HT) at 927 nm, 879 nm and 808 nm ($T > 99\%$), and antireflection (AR) at 1066 nm ($R < 10\%$) is also coated to suppress any parasitic oscillation of the highgain four-level transition. The laser resonator is a linear cavity with a geometric length of 20 mm. A plane mirror M₁ is used as input mirror with HT coating at 879 nm (or 808 nm) and highly reflective coating at 927 nm. The output mirror M₂ is a concave mirror with partially transmissive coating at 927 nm and AR coating at 1066 nm.

3. Experimental results and discussion

The fluorescence spectrum of Nd:GdYNbO₄ around 920 nm is researched with a fiber-coupled optical spectrum analyzer (Ocean Optics, HR4000, 900–1070 nm) with a resolution of 0.1 nm, as shown in figure 2. There are two emission peaks for the Nd:GdYNbO₄ crystal near 921 nm and 927 nm, corresponding to R2 → Z5 and R1 → Z5 transitions. Based on the Fuchtbauer–Ladenburg formula, the stimulated emission cross section for the stronger 927 nm transition is calculated to be $\sim 1.9 \times 10^{-20}$ cm² [22]. It is smaller than those for mature crystals such as Nd:YAG (5×10^{-20} cm²) and Nd:GdVO₄ (6.6×10^{-20} cm²) [10]. Scattering loss is another key factor to evaluate the quality of a novel laser material. An 879 nm LD pumped Nd:GdYNbO₄ continuous-wave four-level laser at 1066 nm is researched to measure the internal loss for Nd:GdYNbO₄. The 1066 nm laser has a plane–plane resonator with a cavity length of 30 mm and a pump beam waist radius of 500 μ m. The threshold pump powers for the 1066 nm laser with output coupler transmissions of 10%–50% are measured and recorded. According to the theory of Findlay and Clay [30], by linear-fitting the experimental data, the internal loss for Nd:GdYNbO₄ crystal is calculated to be 3.8% cm⁻¹. It is 0.2% cm⁻¹ for Nd:YAG crystal, so there is developing space for the crystal quality of Nd:GdYNbO₄. To verify the superiority of direct pumping, the output performance of the Nd:GdYNbO₄ 927 nm laser is investigated with different LDs. The parameters of the 927 nm laser resonator are the same except the pump sources. The output mirror is a concave mirror with a radius of $R = 200$ mm and a transmissivity of $T = 3.6\%$, which is optimized for the 808 nm LD pumped 927 nm laser. The fiber-coupled 808 nm LD works in pulsed operation with a repetition rate of 10 Hz as well as the 879 nm LD. The emission wavelength of the 808 nm LD is dependent on the operating current and temperature with a broader spectrum width of ~ 1 nm. By tuning the temperature of the LD, the absorption efficiency is tuned to ~ 0.6 for Nd:GdYNbO₄ under 808 nm LD pumping, the same as that under 879 nm LD pumping. The pump beam waist is ~ 140 μ m. Figure 3 presents the output energies of the LD endpumped 927 nm laser under 808 nm and 879 nm LD pumping. The threshold pump energies are 17.0 mJ and 48.0 mJ for the 927 nm laser under 879 nm and 808 nm LD pumping. The output energy of the 879 nm LD pumped 927 nm laser reaches 37.4 mJ, corresponding to a slope efficiency of 42.5% and an optical-to-optical efficiency of 35.4% with respect to the absorbed pump power. In comparison, the highest output energy is 24 mJ in the 808 nm LD pumped 927 nm laser with a slope efficiency of 31.0% and an optical-to-optical efficiency of 19.0%. These results indicate that a remarkable efficiency enhancement in the LD-pumped 927 nm laser is achieved by using an 879 nm LD compared with that under 808 nm pumping. The quasi-three-level laser emission with Nd:GdYNbO₄ crystal is measured to be at ~ 927.2 nm and there is not any emission around 1066 nm, as presented in the inset of figure 3. The output characteristics of the 879 nm LD pumped Nd:GdYNbO₄ quasi-three-level laser are investigated with different transmissivities of the output mirror, as shown in figure 4. A plano-concave resonator is utilized in the 927 nm laser with a concave mirror radius of $R = 200$ mm. By using an output mirror with $T = 11.0\%$, a maximum output energy of 42 mJ is obtained at 927 nm with a slope efficiency of 28.6% and an optical-to-optical efficiency of 24%. A higher transmission of the output mirror in the 927 nm laser is preferred under 879 nm LD pumping, which indicates higher gain is realized by direct pumping compared with that under

808 nm LD pumping. By using an output mirror with a transmissivity of $T = 11.0\%$ and a radius of $R = 200$ mm, the 927 nm laser's performance with different pump radii is tested, as shown in figure 5. The slope efficiency of the 927 nm laser with a pump radius of $\omega_p = 200 \mu\text{m}$ is estimated to be 22.0%, lower than that with a pump radius of $\omega_p = 140 \mu\text{m}$. Tight pumping is required for the quasi-three-level transition to overcome reabsorption losses brought by the population in the lower laser level. On the other hand, a small pumping radius would lead to serious thermal effects, which are negligible in pulsed operation at 10 Hz for its low duty cycle. To research the influence of heat loading on laser performance, the repetition rate of the 879 nm LD is changed with a constant pulse width of 2 ms. The duty cycle of the pumping source is 2% at 10 Hz and increases to 20% at 100 Hz. As the output spectrum of the 879 nm LD is stabilized by the VBG, the absorption coefficient is not changed and only the heat loading on the laser medium affects the 927 nm laser's performance. The beam quality factors of the 927 nm laser at different repetition rates are measured by using the traveling knife-edge method [31]. Table 1 gives an overall comparison of the output characteristics for the 927 nm laser at different pumping repetition rates. Pump power saturation appears at repetition rates of 40 Hz and 100 Hz due to higher heat loading. The maximum single-pulse energy decreases from 42 mJ at 10 Hz to 11.3 mJ at 100 Hz. As the incident pump average power increases with the repetition rate, a maximum average output power of 1.13 W is obtained at 100 Hz with an optical-to-optical efficiency of 6.5% and a beam quality factor of $M_2 = 2.0$. At 10 Hz, the beam quality factor of the 927 nm laser is measured to be $M_2 = 1.7$. The beam spatial distributions of the 927 nm laser under 879 nm LD pumping at different repetition rates are also measured by a laser beam analyzer (LBA-712PC-D, Spiricon Inc.), as shown in figure 6. The laser distributions for the 927 nm laser at different repetition rates have good symmetry in both directions. When the repetition rate increases, the beam distribution degrades and the boundary of the laser intensity distribution is fuzzy at 100 Hz, which may be related to the increased losses at higher pumping power [32]. Further energy enhancement of the LD-pumped 927 nm laser based on $4F_{3/2} \rightarrow 4I_{9/2}$ with the Nd:GdYNbO₄ crystal would be expected by improving crystal quality and optimizing the crystal's parameters.

4. Conclusion

In conclusion, we have demonstrated an efficient 879 nm LD end-pumped quasi-three-level 927 nm laser with a novel Nd:GdYNbO₄ crystal for the first time. The fluorescence spectrum of Nd:GdYNbO₄ around 927 nm is researched for this novel crystal. Comparison of the 927 nm laser's output characteristics under 808 nm and 879 nm LD pumping is conducted and performance improvement is achieved by using the 879 nm LD. The highest output energy of the 927 nm laser under 808 nm LD pumping is 24.0 mJ with a slope efficiency of 31.0% and an optical-to-optical efficiency of 19.0%. By optimizing the laser parameters, a maximum output pulse energy of 42.0 mJ at 927 nm is achieved at 10 Hz with an optical-to-optical efficiency of 24.0%. The influence of heat loading on the LD-pumped 927 nm laser is researched by changing the repetition rate of the pump source. The average output power reaches 1.13 W at 100 Hz for the Nd:GdYNbO₄ quasi-three-level 927 nm laser. These results indicate that Nd:GdYNbO₄ is a promising material to generate laser around 900 nm.

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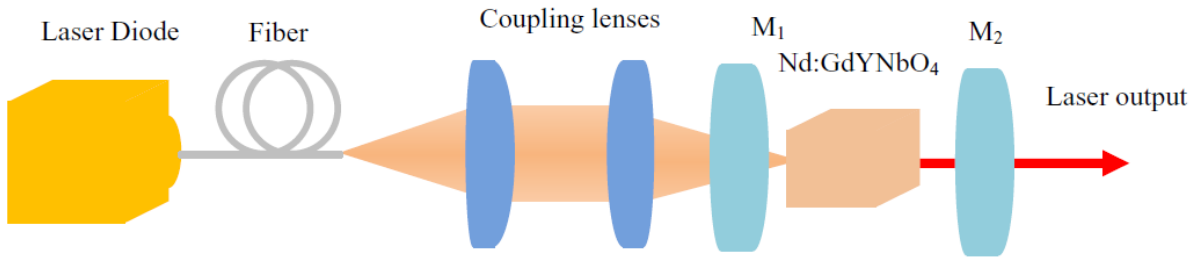


Figure 1. Experimental setup of LD end-pumped Nd:GdYNbO₄ 927 nm laser.

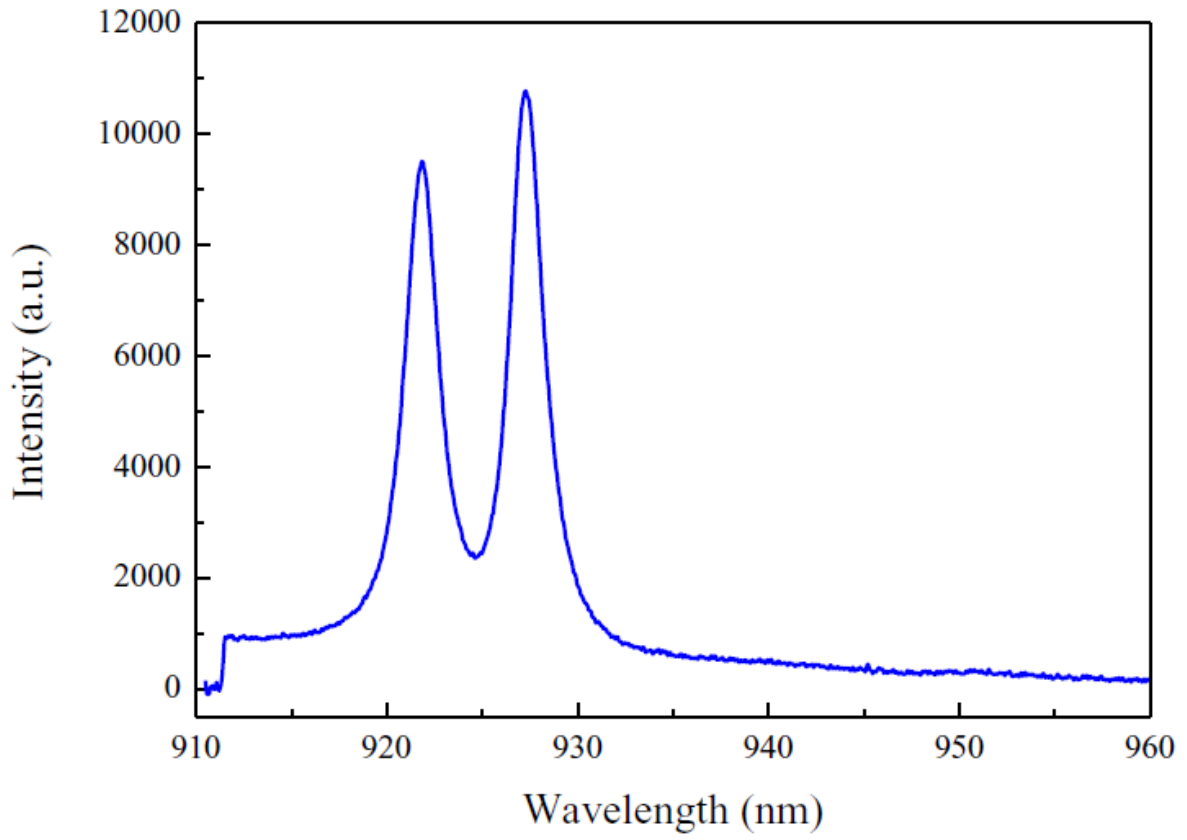


Figure 2. Emission spectrum of Nd:GdYNbO₄ crystal around 920 nm.

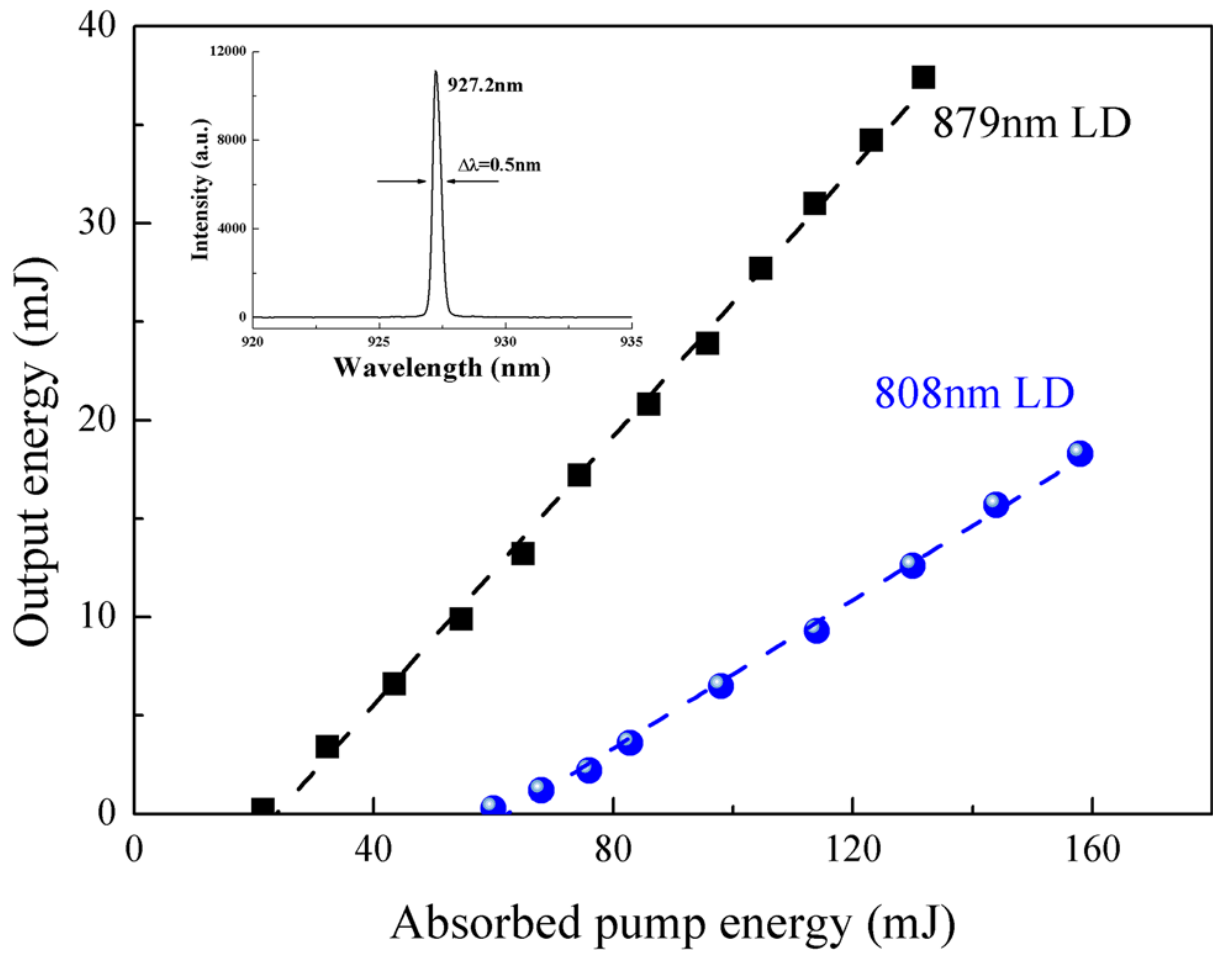


Figure 3. Comparison of 927 nm laser energies with Nd:GdYNbO₄ under 808 nm and 879 nm LD pumping. Output mirror: concave mirror radius of $R = 200\text{ mm}$, $T = 3.6\%$. Insertion: output spectrum of 927 nm laser.

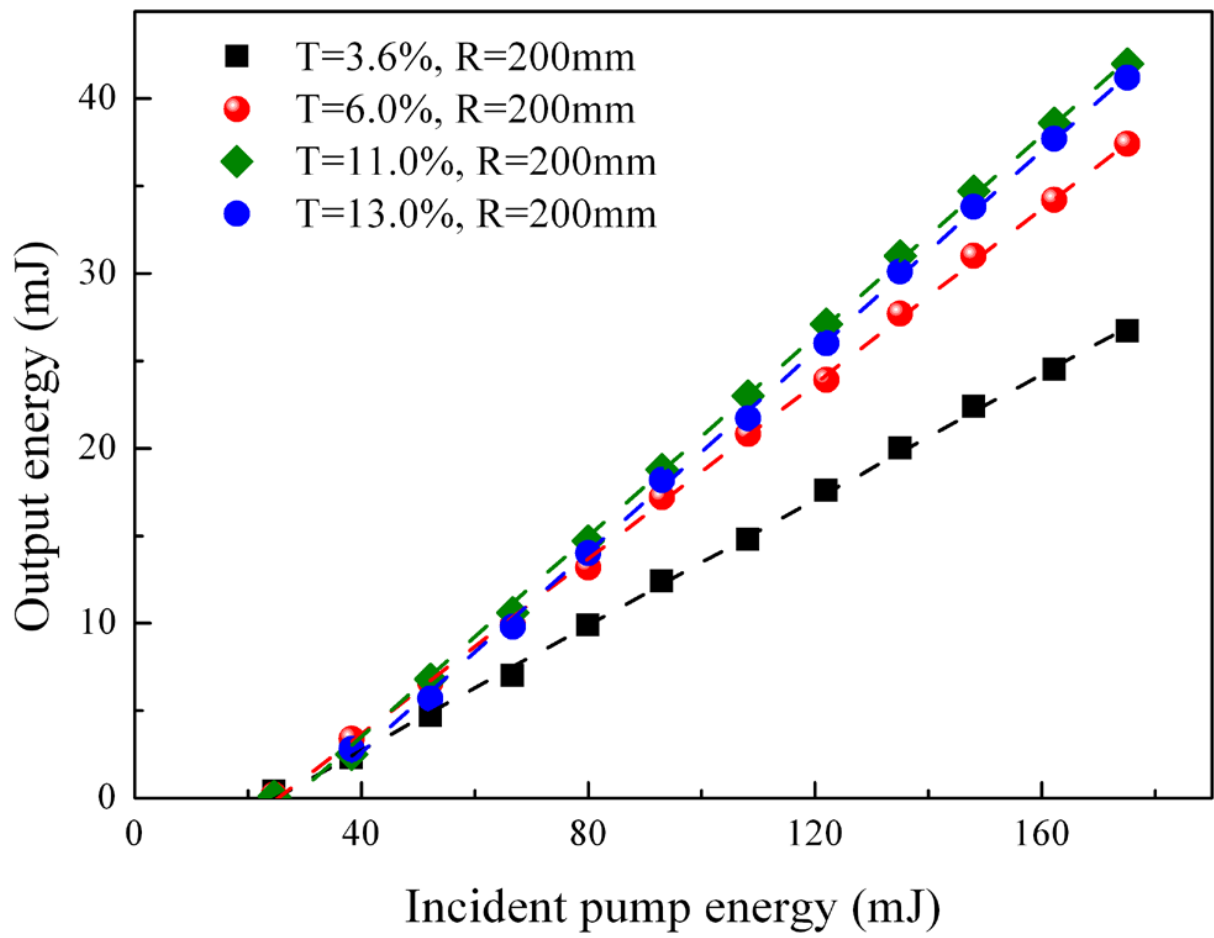


Figure 4. Comparison of 879 nm LD pumped 927 nm laser output performance with different output coupling mirrors.

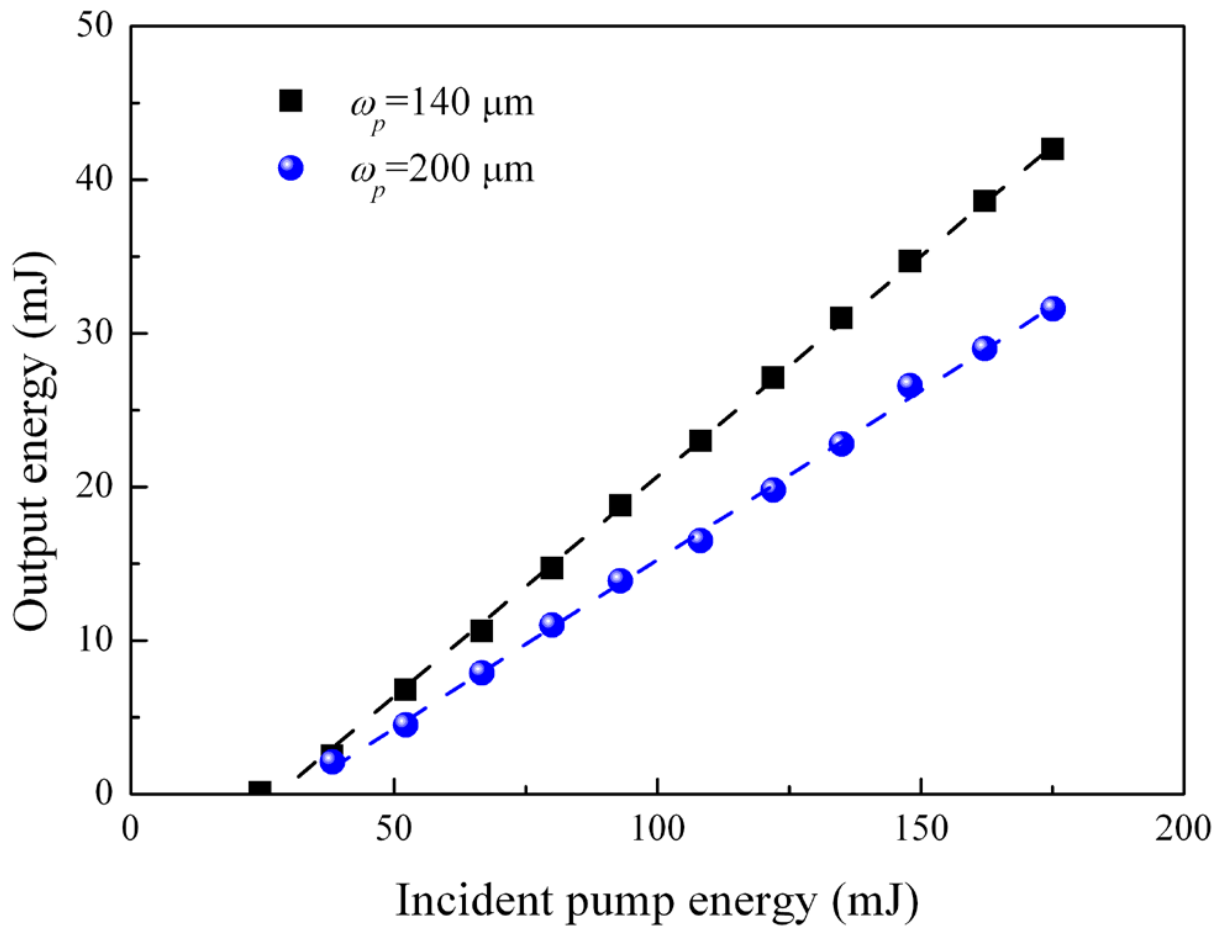


Figure 5. Output energies of 879 nm LD pumped 927 nm laser versus incident pump energy with different pump radii.

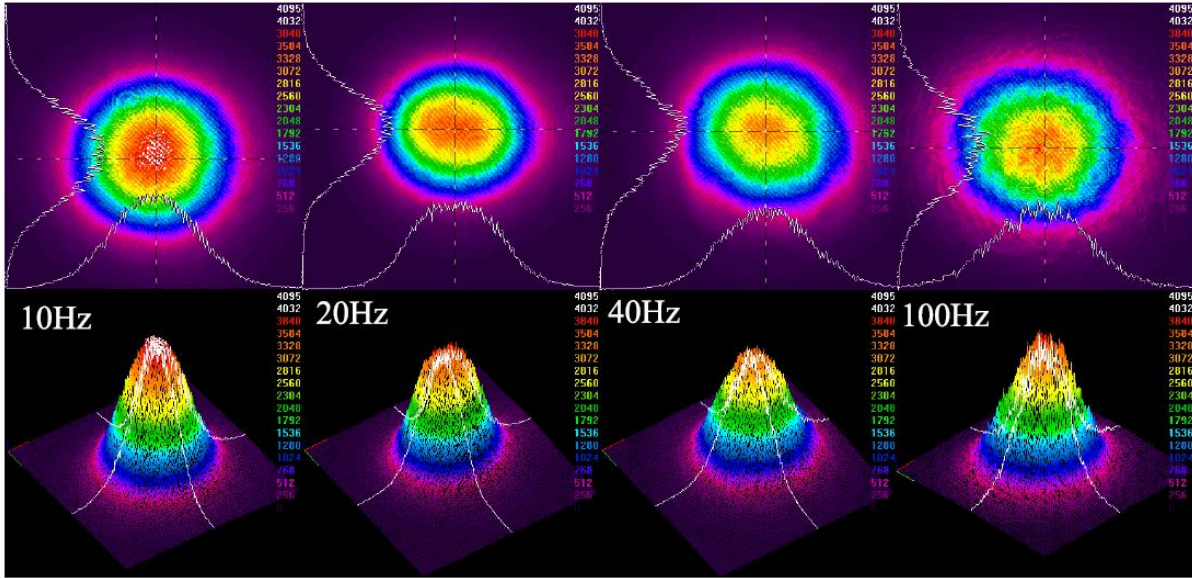


Figure 6. Beam distribution of 927 nm laser under 879 nm LD pumping at different repetition rates.

Pumping repetition rate	10 Hz	20 Hz	40 Hz	100 Hz
Maximum output energy (mJ)	42.0	38.0	26.0	11.3
Maximum average power (mW)	420	760	1040	1130
Optical-to-optical efficiency	24.0%	21.7%	14.8%	6.5%

Table 1. Output characteristics of 879 nm LD pumped 927 nm laser at different pumping rates.