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EXPERIMENTAL STUDY OF THE PULSE ENERGY OF PULSED LD-PUMPED ACOUSTO-OPTICALLY *Q*-SWITCHED TM:YAG LASERS

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Abstract

We study a pulsed LD-pumped high-energy acousto-optically (AO) Q-switched Tm:YAG laser. The output pulse energy is mainly influenced by the output energy at free running and the energy-extraction efficiency under Q-switching operation. The output energy at free running can be improved by optimizing the parameters of the pump source, laser cavity, and laser medium. We show that, in order to avoid the insufficiency or waste of the population inversion and obtain higher energy-extraction efficiency, a proper pumping width and opening time of the Q switch can be found.

Keywords: diode-pumped lasers, acousto-optically Q switching, Tm:YAG.

1. Introduction

2 μm lasers have attracted much attention for numerous applications ranging from remote sensing and medicine to laser radars [1–4]. Single-doped Tm^{3+} laser media are used for obtaining a high-power 2 μm laser output under the LD pumping. A Tm:YAG is extensively used due to its good thermo-mechanical property, high doping concentration, long fluorescence lifetime, and so on [5]. However, the thermal population of the lower laser level affects the laser characteristics of quasi-three-level Tm:YAG laser systems. To improve the laser performance and LD parameters, the laser material and cavity should be designed and optimized carefully. In recent years, there were some reports on continuous-wave (CW) Tm:YAG lasers [6–9]. In 2002, a 150 W continuous-wave Tm:YAG laser was reported in [10] using the compound parabolic concentrator. It is difficult to realize high-energy Q-switched Tm:YAG-laser operation because of the lower gain and higher saturable reabsorption losses. In 2008, a Q-switched 2.013 μm Tm:YAG laser was achieved with the pulse energy and pulse width equal to 4 mJ and 80 ns, respectively, at a repetition frequency of 100 Hz, with a $ZnGeP_2$ optical parametric oscillator (ZGP-OPO)

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as a pump source generating mid-IR 3–5 μm radiation [11]. For accurate wind-velocity measurements, commercial aircraft safety, and global wind monitoring, Tm:YAG lasers with high pulse energy are required to achieve a long distance transmission. At the same time, Tm:YAG lasers with a long pulse width are also required to achieve the narrow transform-limited bandwidths, which is needed to measure the wind velocity within ± 1 m/s [12]. In other words, Tm:YAG lasers with high pulse energy and long pulse width simultaneously are needed for applications in global wind monitoring and so on.

To realize high output energies, the cavity length should be as short as possible to reduce the cavity losses; however, in this case, the pulse width will become shorter. To solve this contradiction, impact factors of the output energy should be studied in detail. Pulsed LD pumping is a good method to relieve the serious thermal effect in Tm:YAG lasers. The laser performance can be kept even when the cavity is long.

In this paper, we study in detail a pulsed LD-pumped acousto-optically Q-switched Tm:YAG laser. The output pulse energy is mainly influenced by the output energy at free running and the energy-extraction efficiency at pulsed operation. The output energy at free running can be improved by optimizing the parameters of the pump source, laser cavity, and laser medium. We show that, in order to avoid the insufficiency or waste of the population inversion and obtain higher energy-extraction efficiency, a proper pumping width and opening time of the Q switch can be found.

2. Theoretical Analysis

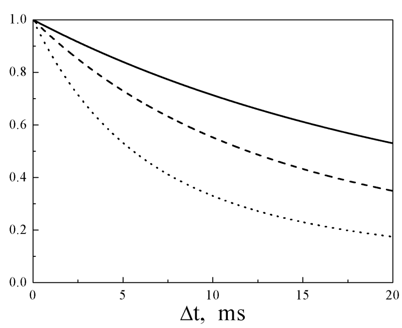

Fig. 1. Dependences of η on Δt, where $\tau = 13.9$ ms (solid curve), 7.5 ms (dashed curve), and 3.5 ms (dotted curve).

At acousto-optically Q-switched laser operation, the single-pulse energy E of the laser output is mainly influenced by two factors, one is the output energy at free running, and the other is the conversion efficiency from free running to Q-switched operation, which is called the energy-extraction efficiency η at pulsed pumping, namely,

$$\eta = \frac{\tau}{\Delta t}\left[1 - \exp\left(-\Delta t/\tau\right)\right], \tag{1}$$

where τ is the lifetime of the upper laser level and Δt is the pump width.

To take into account the influence of τ, we consider the relation between η and Δt (see Fig. 1). We see that η increases with increase in τ and decrease in Δt. In other words, at pulsed pumping, E is influenced not only by f, but also by Δt. When Δt is about half of τ, the pumping availability is more than 0.8. For Δt less than τ, the stored-energy efficiency does not decrease due to the amplified spontaneous emission (ASE) of the particles at the upper laser level. Therefore, since a laser medium has a longer upper-laser-level lifetime, higher output energies can be obtained at a lower repetition rate.

3. Experimental Setup

The experimental setup is shown in Fig. 2.

A fiber-coupled pulsed LD is used as a pump source, whose maximum peak power is 30 W. The central output wavelength of the LD can be turned to 785 nm, which coincides with the absorption peak of Tm^{3+}

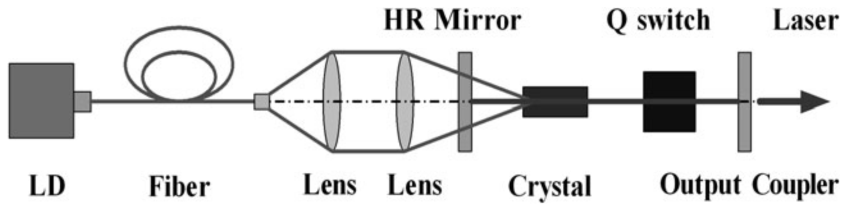

Fig. 2. Schematic of the experimental setup.

by changing the LD temperature. The diameter and numerical aperture of the fiber core are 400 μm and 0.22, respectively. The LD beam is shaped and focused by a series of convex lenses. The mode matching between the pumping and oscillating lasers is optimized by changing the radius and location of the pump beam waist.

A Tm:YAG rod with a doping concentration of 3.5 at.% and dimensions of $\varnothing\, 3\times 8$ mm^3 is employed as the gain medium. The facets are polished to be plane and parallel and are coated with antireflection near 785 nm and 2.01 μm. The input mirror, a convex one with a radius of curvature of -300 mm, is coated with high reflection at 2.01 μm ($R > 99.5\%$) and high antireflection at 785 nm ($R < 0.5\%$). The convex mirror helps to provide a partial compensation of the thermal lens in the laser rod. A concave mirror with a radius of curvature of 300 mm is used as the output coupler.

The cavity length and the transmission of the output coupler are changed to optimize the laser performance. A fused-silica acousto-optical Q switch with a length of 46 mm is used to produce the Q-switching operation. A monochrometer (300 mm focal length, 300 lines/mm grating blazed at 2000 nm) is used to keep the Tm:YAG laser wavelength constant. The pulsed laser is detected by an InGaAs detector connected with a Tektronix TDS3032B digital oscilloscope.

4. Experimental Results and Discussion

4.1. Laser Performance at Free Running

To improve the output energy of the acousto-optically Q-switched laser, one should increase the output energy at free running, which is mainly influenced by the parameters of the pump source, laser cavity, and laser medium.

4.1.1. Pump Source

The output energy of a Tm:YAG laser versus the pumping repetition rate is shown in Fig. 3 at $L = 0.32$ m, $T = 4\%$, and $\Delta t = 10$ ms. With increase in the repetition rate, the output energy and slope efficiency decrease. When the repetition rate is below 10 Hz, this phenomenon is not observed. However, there is a significant decrease in the output energy when the repetition rate is higher than 25 Hz. One can conclude that the thermal effect cannot be effectively released at higher repetition pumping. At 40 Hz, the slope efficiency is lower than 11%, and the output energy decreases suddenly when the pump energy is higher than 300 mJ. Finally, the laser operation is finished due to the serious thermal effect resulting in the instability of the laser cavity.

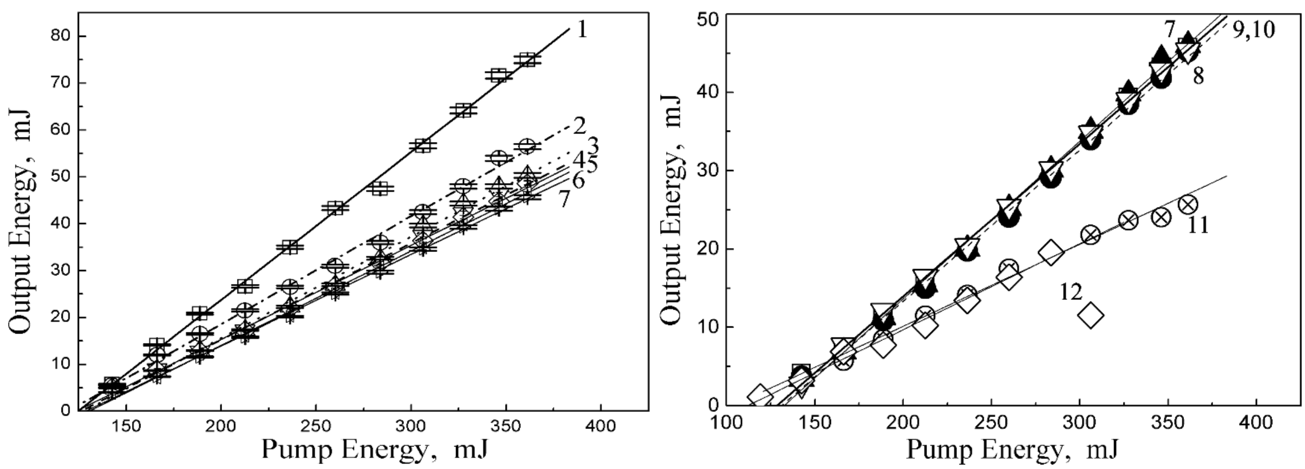

Fig. 3. Output energy versus the pump energy under different pumping repetition rates at 1.2 Hz and $\eta = 31.45\%$ (1), 2.2 Hz and $\eta = 23.04\%$ (2), 2.0 Hz and $\eta = 21.61\%$ (3), 4.0 Hz and $\eta = 20.59\%$ (4), 5.0 Hz and $\eta = 20.09\%$ (5), 6.0 Hz and $\eta = 20.17\%$ (6), 10.0 Hz and $\eta = 19.51\%$ (7), 15.0 Hz and $\eta = 19.33\%$ (8), 20.0 Hz and $\eta = 20.18\%$ (9), 25.0 Hz and $\eta = 19.51\%$ (10), 30.0 Hz and $\eta = 10.47\%$ (11), and 40.0 Hz and $\eta = 10.99\%$ (12).

4.1.2. Laser Cavity

The laser performance is directly influenced by the laser gain and losses. The losses of a laser cavity mainly consist of the geometrical losses, the diffractive losses, the transmission losses, the absorption losses, the insertion losses, and so on. For a stable laser cavity, geometrical losses do not exist. When the laser medium and mirrors with proper sizes are used, the diffractive losses can be also avoided. The transmission losses can be reduced by improving the quality of coating films. To realize a Q-switching operation, a fused silica acousto-optical Q switch is used. It is inserted into the laser cavity, and the insertion losses are unavoidable.

We perform a comparative study using a 2 mm thick antireflecting coating mirror ($R < 0.2\%$@2.01 μm) and 46 mm length acousto-optical Q switch ($R < 0.2\%$@2.01 μm). The experimental results are shown in Fig. 4. When nothing is inserted into the laser cavity, the slope efficiency is 24.2%, and it is reduced to 22.3 and 12.0%, respectively, when the mirror or Q switch is inserted into the laser cavity. We see that the laser performance is sensitive to the insertion losses in the case of low amplification in the Tm^{3+}-doped laser. Therefore, the number of inserted elements in the laser cavity should be reduced to improve the operating efficiency.

The pulsed laser energy is also influenced by the cavity length. As shown in Fig. 5, the output energy is reduced with increase of the cavity length, and the laser can operate stably when the cavity length is 275 mm. However, the mode matching between the pump light and oscillating light deteriorates for the thermal-lensing effect, and the slope efficiency falls down when the cavity length is 330 mm.

The laser performance of a pulse-pumped convex–concave laser cavity with different transmissions of the output coupler is shown in Fig. 6. The cavity length is set at 275 mm. It can be seen that there is an optimum transmissivity for the output coupler. The highest output energy and slope efficiency are obtained using an output coupler of $T = 5.80\%$. Therefore, the transmissivity of the output coupler must be optimized to improve the laser performance.

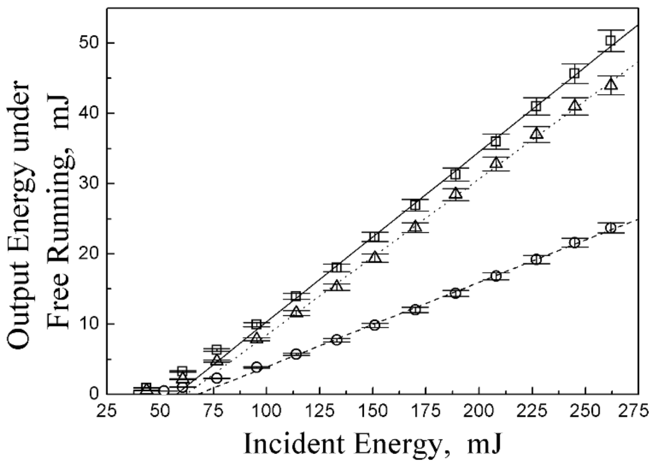

Fig. 4. The laser output energy versus the incident energy at different losses, if there is no element in the cavity (□), with Q switching element in the cavity (○), and with the mirror in the cavity (△).

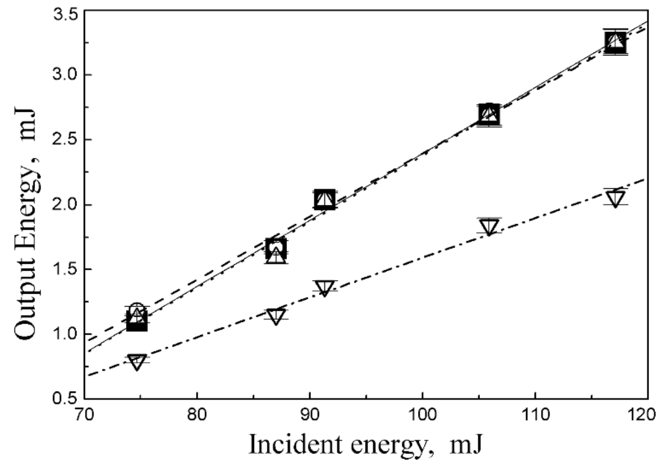

Fig. 5. Output laser performance with different cavity lengths: $L = 120$ mm (■, solid line), 220 mm (○, dashed line), 275 mm (△, dotted line), and 330 mm (∇, dash-dotted line).

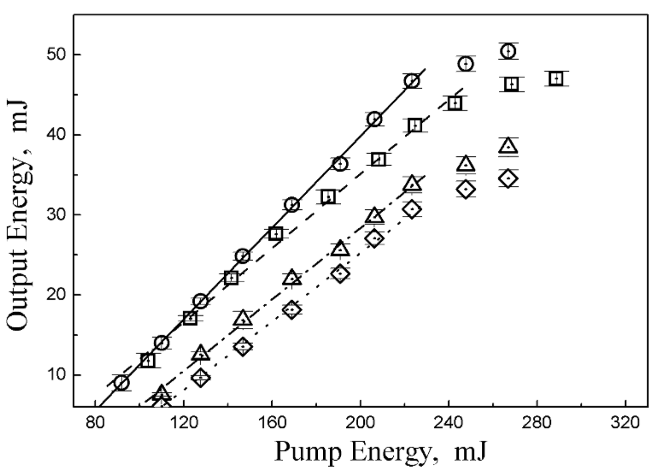

Fig. 6. Output energy versus the input pump energy with different output couplers with $T = 2.97\%$ and $\eta = 23.15\%$ (□, dashed line), $T = 8.74\%$ and $\eta = 22.76\%$ (△, dash-dotted line), $T = 10.00\%$ and $\eta = 21.81\%$ (◇, dotted line), and $T = 5.80\%$ and $\eta = 29.14\%$ (○, solid line).

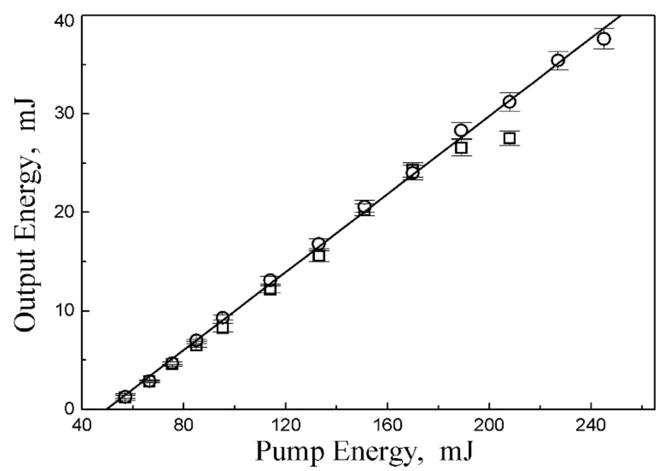

Fig. 7. The laser performance of the composite (○) and conventional (□) Tm:YAG lasers. The solid line is a linear fit of the composite Tm:YAG laser.

4.1.3. Laser Medium

We perform a comparative study of the laser performance using the conventional and composite Tm:YAG laser media. As shown in Fig. 7, the output energy is higher if a composite medium is employed, and this is due to the fact that the thermal distribution is homogenous in the composite medium.

The laser performance of the composite Tm:YAG versus the temperature of the heat sink is shown in Fig. 8. With increase in the temperature, the output energy decreases with a slope of -0.13 mJ/K. To improve the output energy, the absolute temperature in the laser medium should be reduced. However, taking into account the thermal dissipation of the laser medium and the environmental humidity, the temperature should not be reduced too low to avoid dew on the laser medium surface. Therefore, the operating temperature should be controlled and kept at a proper value to make the laser operation efficient and stable.

4.2. Laser Performance at the Q-Switching Operation

The output energy of acousto-optically Q-switching operation is mainly influenced by the energy-extraction efficiency η. In the following, we present the results of our study of the efficiency η for obtaining high-energy outputs.

4.2.1. Output Energy and Energy-Extraction Efficiency

As shown in Eq. (1), for a pulsed pumped acousto-optically Q-switched laser, the energy-extraction efficiency η increases with decrease in the pumping width. Because the pumping width is shorter than the upper-level laser lifetime, the stored energy efficiency is reduced by amplified spontaneous emission of the particles at the upper laser level. Therefore, a high-energy laser output can be obtained. The energy-extraction efficiency η versus the output energy at different pumping widths is shown in Fig. 9. We see that the higher energy-extraction efficiency is obtained at the pumping width of 3.5 and 5 ms. When the pumping width is 12.5 or 15 ms, η is reduced by amplified spontaneous emission for pumping widths longer than the upper-level-laser lifetime, which is predicted by the theory.

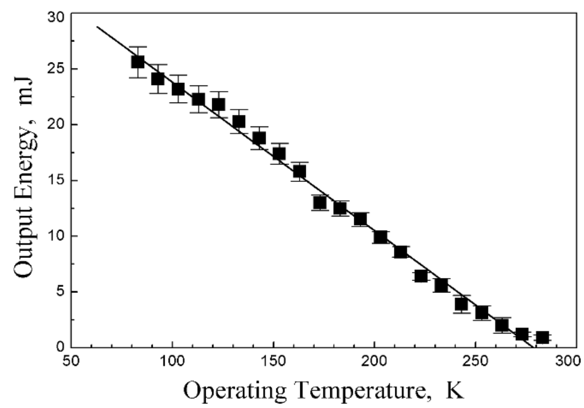

Fig. 8. The output energy versus the copper temperature. The solid line is a linear fit with a slope of -0.13 mJ/K.

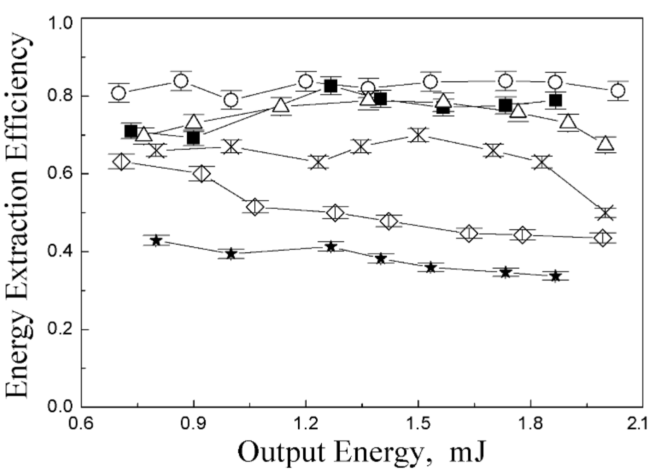

Fig. 9. The energy-extraction efficiency versus the output energy with the experimental data at a pumping width of 3.5 ms (■), 5.0 ms (○), 7.5 ms (△), 10.0 ms (×), 12.5 ms (◇), and 15.0 ms (⋆).

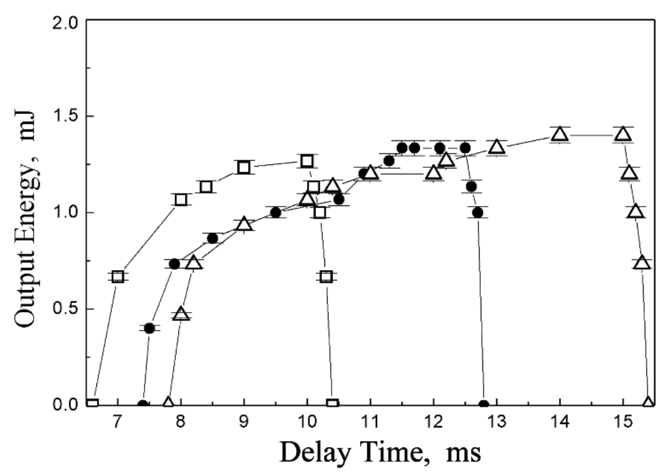

Fig. 10. The laser output energy versus the delay time of opening the Q switch at a pump pulse width of 10 ms (□), 12.5 ms (●), and 15.0 ms (△).

4.2.2. Output Energy and the Opening Time of the Acousto-Optical Q Switch

The output energy is also influenced by the opening time of the acousto-optical Q switch. As shown in Fig. 10, the highest output energy corresponds to the case where the opening time is equal to the pumping width. If the Q switch is not open when the pump is over, the output energy decreases suddenly due to the amplified spontaneous emission. If the Q switch is open before the pump is over, the output energy also decreases, but this decrease is not substantial if the population inversion is large enough. At a pumping width of 12.5 ms, the output energy increases from 0.7 to 1.3 mJ when the Q-switch opening time is between 9.5 and 11 ms, and this fact witnesses that the population inversion is increasing continuously during the whole period. The output energy is kept at 1.3 mJ when the Q-switch opening time is between 11 and 12.5 ms, and this is due to the fact that the population inversion does not increase during this period. In other words, although there is a continuous pumping, unfortunately, this pumping is contributing to the thermal deposition in the laser medium but not to the output energy.

4.2.3. Laser Performance of Q-Switched Tm:YAG Laser

Taking into account all factors mentioned above, we design a bowtie cavity to carefully relieve the thermal effect of the Tm:YAG laser. We use the 46 mm long fused-silica acousto-optical Q switch. The total cavity length is about 0.3 m, and the transmission of the output coupler is 3.5%. We employ a Tm:YAG laser crystal with doping concentration of 3.5% Tm with 3 mm diameter and 8 mm length as an active segment. Undoped YAG crystals with 3 mm diameter and 4 mm length are connected with the pumped surface of the active crystal. To take care for thermal dissipation and avoid the dew on the laser crystal surface, one must control the operating temperature at a proper value to provide an efficient and stable laser operation. The temperature of the crystal is measured on the surface of the copper, which is the holder of the crystal cooled by a thermo-electric (TE) cooler. The temperature is fixed at 290 K, with a controlling definition of 0.07 K. The pump source is a pulsed fiber-coupled pulsed-laser-diode with a peak power of 30 W; its wavelength is tuned to 785 nm, coinciding with the absorption peak of the Tm:YAG crystal. The fiber core has diameter 400 μm and numerical aperture 0.22. At a pump pulse width of 10 ms and a repetition rate of 20 Hz, we obtain an output energy equal to 4.6 mJ with a pulse width of 179.2 ns. At a pump pulse width of 10 ms and a repetition rate of 20 Hz, the output energy is equal to 4.6 mJ with a pulse width of 179.2 ns. At a pump pulse width of 5 ms and a repetition rate of 100 Hz, the output energy is equal to 3.57 mJ with a pulse width of 184.4 ns.

5. Summary

We presented a detailed study of a pulsed LD pumping acousto-optically Q-switched Tm:YAG laser. The single pulse energy is mainly influenced by the output energy at free running and the energy-extraction efficiency at pulsed operation. The output energy can be improved at free running, that can be achieved by optimizing the pump source, laser cavity, and laser medium. To increase the energy extraction efficiency, one must choose a proper pumping width, and the opening time of the Q switch should be optimized to provide sufficient population inversion.

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