Study of passive Q-switching for flash-lamp-pumped 1.34-μm Nd:GdVO$_4$ laser

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Received September 14, 2006

The static laser performance of a-growth Nd:GdVO$_4$ crystal (a-cut, $4 \times 4 \times 25$ (mm)) at 1.34 μm pumped by flash-lamp is investigated with different transmissions of output couplers. With the output coupler transmission of $T = 30\%$, the static output energy of 148 mJ is obtained when the pump energy is 35.2 J, and the corresponding electric-optical conversion efficiency is 0.42%. The Q-switched output of lasers with the output wavelength ranging from 1.3 to 1.6 μm can be realized by using Co^{2+}:LaMgAl$_{11}$O$_{19}$ (Co:LMA) as saturable absorber. A flash-lamp-pumped, passively Q-switched Nd:GdVO$_4$ laser with Co:LMA as saturable absorber is demonstrated in plano-concave laser cavity. With the cavity length of 16.3 cm and pump energy of 19.8 J, the single-pulse output energy, pulse width, and peak power are obtained to be 4 mJ, 80 ns, and 5×10^4 W, respectively.

OCIS codes: 140.3540, 140.3580.

Nd:GdVO$_4$ has become a more popular laser crystal with many advantages such as the large stimulated emission cross-section, high absorption coefficient, and high-thermal conductivity along the ⟨110⟩ direction (about 11.7 W·m^{-1}·K^{-1})[1−3]. There is widespread need for the lasers operating near 1.3 μm because they coincide with the transmission window of silica optical fibers, and the frequency-doubling of these lasers supplies an effective way to generate red lasers.

Passively Q-switched lasers, due to the advantages of miniature, simplicity, compactness, high efficiency, and low cost[4], have wide applications in the fields of industry, medicine, basic scientific researches, and so on. Saturable absorbers like Co-doped crystals of LiGa$_5$O$_8$, MgAl$_2$O$_4$, LaMgAl$_{11}$O$_{19}$, and ZnS can be used as passive Q-switch in the lasers with output wavelength ranging from 1.3 to 1.6 μm[5−8]. Saturable absorber Co:LMA for Q-switching of the flash lamp-pumped 1.34-μm Nd:YAlO$_3$ laser[5] and diode-pumped 1.34-μm Nd:GdVO$_4$ laser[9] has been reported. Because the stimulated emission cross-section of Nd:GdVO$_4$ at 1.34 μm is comparable to the value of σ_{gs} (ground-state absorption cross-section of Co:LMA), intracavity focusing is necessary to realize the passive Q-switching. So we select a concave with relatively smaller radius of curvature of 250 mm to get the smaller spot area of oscillating lights on the Co:LMA.

In this paper, we have demonstrated the static output performance of a flash-lamp-pumped a-growth Nd:GdVO$_4$ laser operating at 1.34 μm with the flat-flat laser cavity. Experimental results show that a-growth Nd:GdVO$_4$ crystal has good output performance of static laser operating at 1.34 μm. We have also realized, for the first time to our knowledge, the passive Q-switching at 1.34 μm with Co:LMA as saturable absorber by focusing in a plano-concave laser cavity. Under our experimental conditions, the single-pulse output is obtained at lower pump energy. The corresponding pulse energy, pulse width, and peak power are 4 mJ, 80 ns, and 5×10^4 W, respectively.

The experimental setup of Q-switched laser cavity structure is schematically given in Fig. 1. The laser cavity is composed of a concave mirror M$_1$ ($R = 250$ mm) with high-transmission (HT) coating at 1.06 μm and high-reflection (HR) coating at 1.34 μm, and a plane output coupler M$_2$ with HT at 1.06 μm and partial-reflection at 1.34 μm. In order to decrease the loss of the oscillating light of 1.34 μm in cavity and prevent the self-oscillation of 1.06 μm in Nd:GdVO$_4$ crystal, both sides of the crystal are coated with HT coating at 1.06 and 1.34 μm. The Nd:GdVO$_4$ crystal ($4 \times 4 \times 25$ (mm), 0.52 at.-% Nd-doped), placed close to M$_1$, is pumped in a 50-mm-length single silver-coated elliptical cylinder reflector by a $\phi 5 \times 50$ (mm) xenon flash-lamp. The sample of Co:LMA, placed close to M$_2$, is $4 \times 4 \times 0.5$ (mm) and 1 at.-% Co-doped, but there is no HT coating at 1.34 μm on its both sides. EPM2000 energy meter (Molectron Corp., USA) and TDS3032B digital oscilloscope (Tektronix Inc., USA) are used to measure the output energy and laser pulse width, respectively.

A plane mirror with HT coating at 1.06 μm and HR coating at 1.34 μm replaces the concave mirror M$_1$ in Fig. 1 and the Co:LMA is removed from the cavity. With the 15-cm-length flat-flat cavity, the static laser performance is investigated. The variation of output laser energy versus pump energy for different transmissions ($T = 10\%$, 30% and 40%) of output couplers is plotted in Fig. 2.

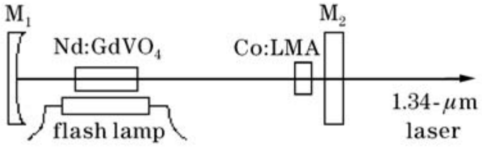

Fig. 1. Schematic diagram of the experimental setup of Q-switched laser cavity structure.

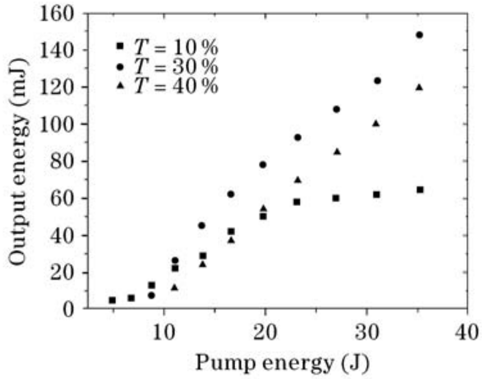

Fig. 2. Static output laser energy versus pump energy with different output coupler transmissions.

It is well known that the threshold pump power for a four-level system is given by[10]

$$P_{\mathrm{th}} = (L - \ln R)\frac{Ah\nu_{\mathrm{p}}}{2\sigma\tau\eta_{\mathrm{ge}}}, \tag{1}$$

where P_{th} is the threshold pump power, L is the intracavity round-trip dissipative optical loss, R is the reflectivity of output mirror, A is the cross-section of Nd:GdVO$_4$ crystal, $h\nu_{\mathrm{p}}$ is the single pump photon energy, σ is the stimulated emission cross-section of gain medium, τ is the fluorescence lifetime of the gain medium, and η_{ge} is the efficiency factor. The σ and τ values of Nd:GdVO$_4$ crystal at 1.34 μm are about 1.95×10^{-19} cm^2[11] and 100 μs, respectively. According to Eq. (1) we can find that when the value of $\sigma \times \tau$, or R, is relatively larger, the lower threshold pump power can be expected. Figure 2 shows that the output laser energy increases almost linearly with the pump energy for these output coupler transmissions. For $T = 10\%$, the threshold pump energy is 3.2 J, but the curve is saturated when the pump energy reaches 23.5 J because of the lower output coupler transmission. According to the formula of optimum output coupler transmission $T_{\mathrm{out}} = (\sqrt{2g_0 l/L} - 1)L$, where g_0 is the round-trip small signal power gain and l is the length of gain medium, the higher transmission of output coupler is required when g_0 or pump energy increases. But the increase of output coupler transmission, corresponding to increasing the loss of the resonator, will result in the higher threshold pump energy and the lower electric-optical conversion efficiency. For $T = 40\%$, although the slope efficiency of the curve is higher, it also has the highest threshold pump energy of 8.3 J, and the electric-optical conversion efficiency is relatively lower. The output curve of $T = 30\%$ has the lower threshold pump energy of 6.2 J and higher slope efficiency, and the saturation does not occur all the time. Under the pump energy of 35.2 J, the output laser energy is 148 mJ, and the corresponding electric-optical conversion efficiency is 0.42%.

Figure 3 shows the non-polarized room-temperature absorption spectra of Co:LMA crystals[9]. The ground state energy level ^4F of a free ion Co^{2+} is split into three levels of $^4T_1$, $^4T_2$, and $^4A_2$ by the tetrahedral crystal field. The strong absorption band centered at 591 nm is as a result of the spin- and electric-dipole-allowed $^4A_2\left(^4F\right) \rightarrow {}^4T_1\left(^4P\right)$ transition. This transition leads to the Co:LMA crystal appearing blue color. The broad near-infrared absorption band located at 1030—1660 nm is due to the $^4A_2\left(^4F\right) \rightarrow {}^4T_1\left(^4F\right)$ transition and indicates potential application of the Co:LMA crystal as a saturable absorber Q-switch for the 1.3—1.6 μm lasers. The complicated structure of the absorption bands is explained by splitting of the $^4T_1(^4P)$ and $^4T_1(^4F)$ states of Co^{2+} ions by tetrahedral crystal field of oxygen slightly distorted. It can be seen that the non-polarized absorption spectra almost have the same shape when the non-polarized light through the crystal wafers along the X$_2$ and X$_3$ crystallophysical directions in the visible absorption band except that the absorption coefficient increases with the cobalt ions concentration, while there is a little difference in the near-infrared absorption band. The absorption coefficients at 1.34 μm were 5.79 cm^{-1} (1 at.-% Co:LMA X$_2$), 6.27 cm^{-1} (1 at.-% Co:LMA X$_3$), 3.32 cm^{-1} (0.5 at.-% Co:LMA X$_2$), and 3.51 cm^{-1} (0.5 at.-% Co:LMA X$_3$). It can be seen that the absorption coefficients increase almost linearly with the concentration of Co^{2+} ions, and the ground-state absorption cross-section of Co:LMA crystal was calculated to be 2.6×10^{-19} cm^2.

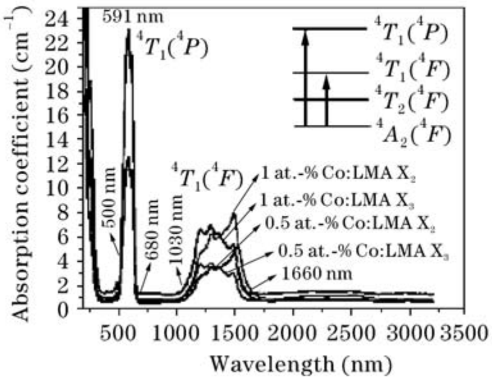

Fig. 3. Room temperature absorption spectra of Co^{2+}: LaMgAl$_{11}$O$_{19}$ crystal.

For optimization of passive Q-switching, sometimes, the gain medium with large stimulated emission cross-section is not helpful when designing the laser setup, because the Q-switch works well only if the saturation in the absorber occurs before the gain saturation (the second threshold condition)[12]. According to the analysis of the coupled rate equations, the criterion for good passive Q-switching is given by[12]

$$\frac{\ln\left(\frac{1}{T_0^2}\right)}{\ln\left(\frac{1}{T_0^2}\right) + \ln\left(\frac{1}{R}\right) + L}\frac{\sigma_{\mathrm{gs}}}{\sigma}\frac{A}{A_{\mathrm{S}}} > \frac{\gamma}{1-\beta}, \tag{2}$$

where T_0 is the initial transmission of saturable absorber, A/A_{S} is the ratio of the effective area in the gain medium to that in the saturable absorber, σ_{gs} is the ground-state absorption cross-section of saturable absorber, γ is the inversion reduction factor ($\gamma = 1$ and $\gamma = 2$ correspond to four-level and three-level systems), and β is the ratio of the excited-state absorption cross-section to that of the ground-state absorption in the saturable absorber.

The stimulated emission cross sections at 1.319 μm of Nd:YAG crystal is 8.7×10^{-20} cm^2 which is relatively smaller compared with the σ_{gs} value of Co:LMA. So the ratio of $\sigma_{\mathrm{gs}}/\sigma$ is relatively larger and the second threshold condition can be satisfied easily in a flat-flat cavity. But the σ value of Nd:GdVO$_4$ crystal operating at 1.34 μm is about 1.95×10^{-19} cm^2, which is comparable to the σ_{gs} value of Co:LMA. If the condition of Eq. (2) is satisfied, the A/A_{S} must be higher than 1.87. For the flat-flat laser cavity, the $A/A_{\mathrm{S}} = 1$ cannot satisfy with the second threshold condition. In our experimental process, Q-switched output pulses are not obtained under any pump energy by placing a Co:LMA crystal of initial transmission $T_0 = 78\%$ in the flat-flat laser cavity. So the intracavity focusing is needed to increase the value of A/A_{S}. A concave mirror with radius of curvature of 250 mm replaces the plane mirror and the cavity length changes to be 16.3 cm. In order to get larger A/A_{S} value, Nd:GdVO$_4$ and Co:LMA crystals are placed close to the concave mirror and the output mirror, respectively, because the beam waist of oscillating lights is located on the output coupler in the plano-concave laser cavity. According to $ABCD$ laws of Gaussian beam[13], the ratio of the spot area of oscillating lights on the concave mirror to that on the output coupler can be calculated to be 2.93. It is much higher than the critical A/A_{S} value (1.87) in Eq. (2), so the condition of passive Q-switching is satisfied. In our experiment, the Q-switched laser pulses begin to appear when the pump energy of 13.8 J reaches.

With the output coupler transmission of 30%, cavity length of 16.3 cm, and initial transmission $T_0 = 78\%$ of Co:LMA, Fig. 4 shows the variation of Q-switched pulses output energy versus the pump energy. We can see from that the output energy increases with the increase of the pump energy. When the flash-lamp pump energy is lower than 20 J, single-pulse is obtained; when the pump energy is higher than 20 J, the output pulses are multi-pulses. Figure 5 shows the variation of single-pulse width versus the pump energy. We can see from it that the pulse width decreases with the increase of pump energy. Because the oscillating light power density in the resonator increases with increase of pump energy, the Co:LMA saturable absorber is rapidly saturated at relatively larger pump energy, so the pulse width decreases gradually. With the pump energy of 19.8 J, the largest single-pulse energy is 4 mJ, and the corresponding pulse full-width at half maximum (FWHM) and peak power are 80 ns, 5×10^4 W, respectively. At this time, the oscillating light spot on the Co:LMA and power density in the resonator are approximately 5×10^{-3} cm^2, 2.3×10^7 W/cm^2, respectively.

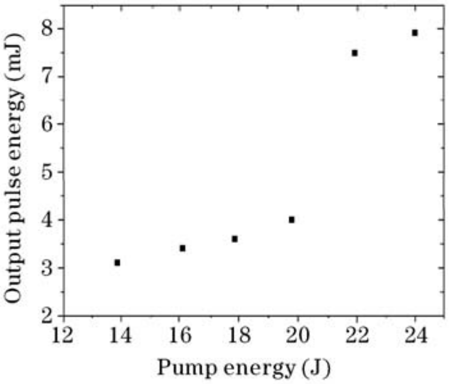

Fig. 4. Q-switched pulse energy versus pump energy with output coupler transmission of 30% and cavity length of 16.3 cm.

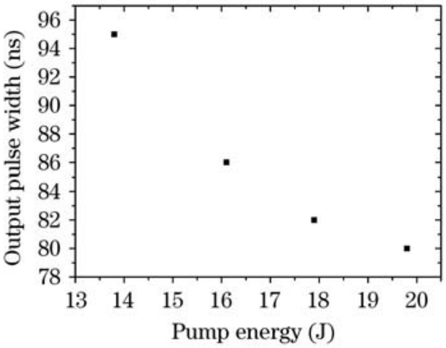

Fig. 5. Q-switched single-pulse width versus pump energy with output coupler transmission of 30% and cavity length of 16.3 cm.

Compared with other laser crystals, such as Nd:YAG, the fluorescence lifetime of Nd:GdVO$_4$ crystal is relatively short (about 100 μs) and not helpful to store the inverted population on upper level, so it makes passively Q-switched Nd:GdVO$_4$ pulsed laser generate multi-pulses. For passive Q-switching, the factor α can be used to denote whether the passive absorber can rapidly saturate or bleach into a high transmission state. The expression is given by[14]

$$\alpha = \frac{\sigma_{\mathrm{gs}} A}{\gamma \sigma A_{\mathrm{S}}}, \tag{3}$$

if α is too large, the saturable absorber is very easy to saturate and the laser output with multi-pulses is generated easily; on the contrary, if α is relatively smaller, the saturable absorber is hard to saturate, so the Q-switching is hardly realized. In our experiment, because the σ_{gs} and σ are both constant, if we want the perfect Q-switched single-pulse output, a quite appropriate A/A_{S} value must be chosen to balance the realization of Q-switching and the restraining of multi-pulses.

Table 1 shows the threshold pump energy, the A/A_{S},

Table 1. A/A_{S}, α, and Some Parameters of Output Pulses with Three Different Cavity Lengths

Cavity Length (cm)	Threshold Pump Energy (J)	A/A_{S}	α	Pump Energy of 19.8 J	
				Number of Output Pulses	Total Output Energy (mJ)
21.5	9.8	7.14	9.52	5	11.2
18.8	12.3	4.03	5.37	3	6.7
16.3	13.8	2.93	3.91	1	4

and α, the number of output pulses, and total output pulse energy under pump energy of 19.8 J when three different cavity lengths are 21.5, 18.8, and 16.3 cm, respectively. We can see from it that the A/A_S and α increase gradually with the increase of cavity length. The increase of cavity length is helpful to reduce the threshold pump energy and to raise the total output pulse energy, but at the same time, the number of output pulses also increases from 1 to 5.

With flash-lamp pump energy of 19.8 J and cavity length of 16.3 cm, single-pulse profile is shown in Fig. 6 (a). The output pulse energy, pulse width and peak power are obtained to be 4 mJ, 80 ns, and 5×10^4 W, respectively. Figure 6(b) shows the laser output with five-pulses when the pump energy is 19.8 J and cavity length is 21.5 cm.

For a-growth Nd:GdVO$_4$ crystal (a-cut), we have demonstrated the static and dynamic laser output performance at 1.34 μm pumped by flash-lamp. The static results indicate that the laser has lower threshold pump energy and higher electric-optical conversion efficiency because of the larger stimulated emission cross-section of Nd:GdVO$_4$ crystal. The Nd^{3+} doped concentration of the Nd:GdVO$_4$ crystal is 0.52 at.-% in our experiment. For flash-lamp-pumped laser, higher electric-optical conversion efficiency and output pulse energy are expected if Nd^{3+} doping concentration of the Nd:GdVO$_4$ crystal increases. Therefore, there are wide application foregrounds of the medium and high energy laser at 1.34 μm. In this paper, we have also reported the experimental results of the passive Q-switching of Nd:GdVO$_4$ crystal by using a Co:LMA crystal as saturable absorber at 1.34 μm. The method of intracavity focusing is adopted because the stimulated emission cross-section of Nd:GdVO$_4$ at 1.34 μm is comparable to ground-state absorption cross-section of Co:LMA. The factor α, which indicates whether the passive absorber can rapidly saturate, varies with the cavity length, so higher single-pulse energy can be obtained by choosing an optimum cavity length. Although, under our experimental conditions, single-pulse output is only realized under lower pump energy, if the Co^{2+} doping concentration of Co:LMA crystal increases, or its both sides are coated with HT coating at 1.34 μm, single-pulse output with higher pulse energy and shorter pulse width can be expected.

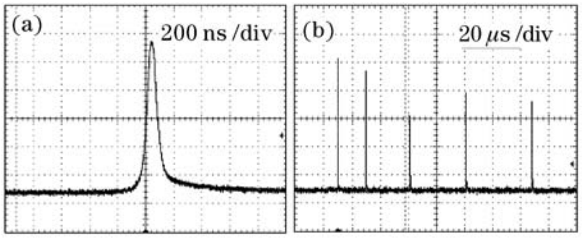

Fig. 6. (a) Single-pulse profile with pump energy of 19.8 J and cavity length of 16.3 cm; (b) Q-switched pulse train with pump energy of 19.8 J and cavity length of 21.5 cm.

This work was supported by the National Natural Science Foundation of China under Grant No. 90201017. H. Zhang is the author to whom the correspondence should be addressed, his e-mail address is hjzhang@icm.sdu.edu.cn.

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