Cr^{2+}:ZnS Saturable Absorber Passively Q-Switched Ho:$LuVO_4$ Laser *

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(Received 4 July 2015)

We report a cw Tm:YAP laser resonantly pumped Ho:$LuVO_4$ laser in passively Q-switched (PQS) mode with Cr^{2+}:ZnS as a saturable absorber (SA). The influence of different transmittances of the output coupler on laser output performance is analyzed. With $T = 50\%$, the maximum PQS average output power of 2.3 W is obtained, corresponding to the slope efficiency and the optical–optical conversion efficiency are 35.1% and 19.8%, respectively. Also, the minimum pulse width of 100 ns is achieved at the maximum pulse repetition frequency of 34.2 kHz. When the maximum cw output power is 2.7 W, the beam quality factor of the horizontal direction $M_x^2 = 1.04$ and the vertical direction $M_y^2 = 1.10$ are obtained. In addition, the central wavelength of the laser output remains to be 2057.5 nm with the output coupler transmittances of 50% and 60% in both cw and PQS operations. The results show that the Cr^{2+}:ZnS can be used as an SA in a Ho:$LuVO_4$ laser around 2-μm wavelength.

PACS: 42.60.Gd, 42.70.Nq, 42.55.Rz DOI: 10.1088/0256-307X/32/10/104208

The mid-infrared spectral region of 2 μm band is in the transparent window of the atmosphere and safety for eyes, which makes 2 μm solid-state lasers show very broad applications in the fields of medical science,[1] environmental monitoring[2] and materials processing.[3] More importantly, 2 μm pulse lasers can be used as pump sources of all-solid mid-infrared and far-infrared band optical parametric oscillator (OPO) and optical parametric amplifier (OPA) to produce broadband tunable laser output in 3–5 μm and 8–12 μm.[4,5]

The passively Q-switched (PQS) laser uses the nonlinear absorption properties of a saturable absorber (SA) to control the laser absorption loss that can realize the laser pulse output. The PQS laser has characteristics such as simple structure, low cost and small size, which makes it receive wide attention.[6,7] SAs for the 2 μm laser mainly include single-walled carbon nanotubes (SWCNTs),[8] graphene[9] and Cr^{2+} doped chalcogenide compounds (including ZnS and ZnSe),[10,11] etc., due to the large accumulation number of SWCNTs, as well as high intracavity loss, which would influence the operating efficiency and stability of the laser. Because the damage threshold of graphene is very low, it cannot obtain a pulse output energy over mJ level. The Cr^{2+} doped chalcogenide compound (including ZnS, ZnSe, etc.) crystal has the advantage of large absorption cross section, high absorption threshold, high hardness and simple level structure, makes it an excellent PQS crystal in the 2 μm laser. Compared with Cr^{2+}:ZnSe, Cr^{2+}:ZnS crystal has a maximum thermal conductivity, minimal thermal optical coefficient, the highest hardness and maximum thermal shock parameters. Therefore, when the PQS laser operates with a Cr^{2+}:ZnS crystal, the internal temperature gradient is small, the thermal lens effect is weak, and the ability to resist rupture is strong. This makes the output performance of the laser more stable.[12]

The tetragonal uniaxial lutetium vanadate $LuVO_4$ crystal belongs to a space group of D_{4h}. Such crystals have high thermal conductivity, high stable chemical property and the mature growth technology, which is easier to be obtained with high quality.[13] At present, mainly $LuVO_4$ laser medium for generating the 2 μm laser output is Tm:$LuVO_4$ and Ho:$LuVO_4$ crystals. In 2011, Yu *et al.* obtained a 1929 nm 1.3 W Tm:$LuVO_4$ cw laser with the slope efficiency of 24.2%.[14] In 2014, Trapani *et al.* used a titanium sapphire laser as the pump source, the cw laser output of Tm:$LuVO_4$ 1 W wide band tunable at room temperature was realized.[15] In the same year, our group used a Tm:YAP solid-state laser as the pump source, a 2074.18 nm Ho:$LuVO_4$ cw laser output at room temperature was achieved with the maximum output power 2.5 W.[16] In 2015, our group reported

*Supported by the National Natural Science Foundation of China under Grant Nos 61308009, 61405047 and 50990301, the China Postdoctoral Science Foundation Funded Project under Grant No 2013M540288, the Fundamental Research Funds for the Central Universities under Grant Nos HIT.NSRIF.2014044 and HIT.NSRIF.2015042, the Science Fund for Outstanding Youths of Heilongjiang Province under Grant No JQ201310, and the Natural Science Foundation of Heilongjiang Province under Grant No LBH-Z14085.

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the performance of the Ho:$LuVO_4$ active Q-switched laser. At 40 kHz repetition frequency, we obtained the maximum average output power of 4.1 W in the central wavelength of 2058.43 nm.[17] However as far as we know, PQS lasers currently used to produce the 2 μm laser output $LuVO_4$ laser medium has not yet been reported. In this work, we first report the peculiarity of the PQS Ho:$LuVO_4$ laser by diode-pumped Tm:YAP lasers.

First, we compare and analyze the performances of the laser with transmittances of the output coupler $T = 50\%$ and 60%. With $T = 50\%$, the maximum average output power of PQS is 2.3 W at the absorbed pump power of 11.6 W, corresponding to the central wavelength of 2057.5 nm. The minimum pulse width of 100 ns with the pulse repetition of 34.2 kHz is obtained at the PQS operation. In addition, in both cw and PQS operations, the output central wavelength of the laser remains at 2057.5 nm with $T = 50\%$ and 60%.

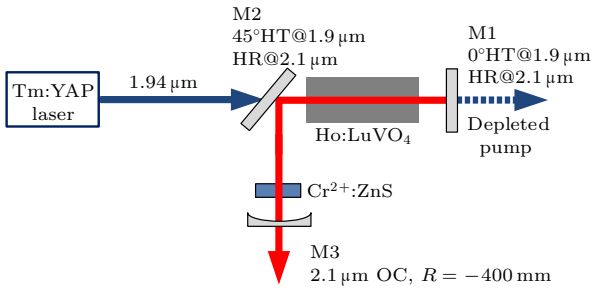


Fig. 1. Experimental setup of the PQS Ho:$LuVO_4$ laser.

The experimental setup is shown in Fig. 1. To evaluate the lasing performance of the Ho:$LuVO_4$ crystal at room temperature, a diode-pumped Tm:YAP laser with the emission wavelength of 1.94 μm is utilized as the pump source, which emits 25 W of output power with the beam quality M^2 of 3.4. The Ho:$LuVO_4$ crystal is 20 mm in length and 3 × 3 mm in cross section, doped with 0.5 at.% Ho^{3+} and antireflection coated at 1.94 μm. The low doping concentration of Ho^{3+} ion will not only improve the Ho^{3+} laser efficiency, but also reduce thermal loading of the laser crystal.[18] Considering the losses of the transmission, the single-pass absorption of the crystal is measured to be 46%. The Ho:$LuVO_4$ crystal is wrapped in indium foil and is clamped in a copper heat-sink held at a temperature of 17℃ with a thermoelectric cooler.

The L-shaped Ho:$LuVO_4$ laser cavity consists of a plane mirror M1 with $R > 99.5\%$ at 2.1 μm and $T > 96.2\%$ at 1.9 μm, a 45° dichroic mirror M2 with $R > 97.7\%$ at 2.1 μm and $T > 97\%$ at 1.9 μm, and an output coupler M3 with a curvature radius of $R = -400$ mm. The physical cavity length is 110 mm. For the PQS operation, the Cr^{2+}:ZnS SA is cut into $9 \times 9 \times 2\,mm^3$ with small signal transmission of 86.3% at 2.1 μm, which is mounted in a copper heat sink and is cooled with circulating water. The distances between Cr^{2+}:ZnS SA and the output coupler is 15 mm. The saturation fluence is 1.1 $J \cdot cm^{-2}$. The calculated TEM_{00} beam diameter is about 360 μm for the PQS operation in the Ho:$LuVO_4$ crystal with an analysis of cold resonator. The beam diameter of the TEM_{00} mode calculated on the Cr^{2+}:ZnS SA is about 730 μm. By using of a 75 mm focal length mode-matching lens, the pump spot size of ∼320 μm in diameter is formed in the Ho:$LuVO_4$ crystal.

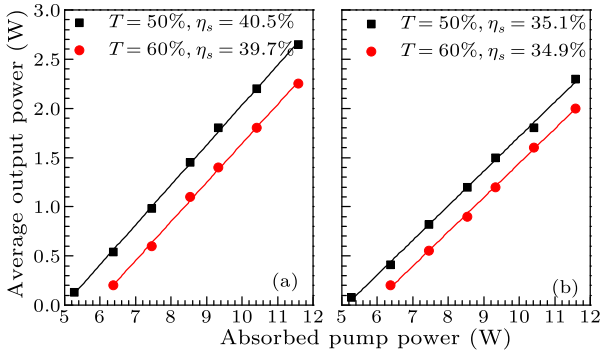


Fig. 2. Average output powers of cw (a) and PQS, and (b) Ho:$LuVO_4$ lasers versus the absorbed pump power.

Figure 2 shows the average output powers of cw and PQS Ho:$LuVO_4$ lasers versus the absorbed pump power. As can be noted from Fig. 2(a), in the cw operation the threshold powers are about 5.3 W and 5.9 W corresponding to the output coupler $T = 50\%$ and $T = 60\%$. The maximal output powers are 2.7 W and 2.3 W for the absorbed pump power of 11.6 W in the crystal with slope efficiencies of 40.0% and 39.7%, respectively, corresponding to the optical–optical conversion efficiencies of 23.3% and 19.8%.

The output performances of the PQS Ho:$LuVO_4$ laser are investigated by inserting the Cr^{2+}:ZnS SA into the cavity. From Fig. 2(b), when the transmittances of output couplers are 50% and 60%, at 11.6 W the absorbed pump power, the maximal output power are 2.3 W and 2 W with slope efficiencies of 35.1% and 34.9%, corresponding to the optical–optical conversion efficiencies of 19.8% and 17.2%, respectively.

The cw and PQS laser spectra are recorded with a spectrum analyzer (BRISTOL INSTRUMENTS 721) at the absorbed pump power of 11.6 W, as shown in Fig. 3. When the Ho:$LuVO_4$ laser is in the cw operation without Cr^{2+}:ZnS in the cavity, the cw laser central wavelength is 2057.5 nm with $T = 50\%$. However, when Cr^{2+}:ZnS is placed into the cavity, the Ho:$LuVO_4$ laser is in the PQS operation, the central wavelength of the output laser pulse is also 2057.5 nm. As for $T = 60\%$, in cw and PQS operations it has no change at the laser central wavelength compared with $T = 50\%$. That is, for $R = -400$ mm ($T = 50\%$ and $T = 60\%$) of the output coupler, the center wavelength of the laser output does not change under the conditions of cw and PQS.

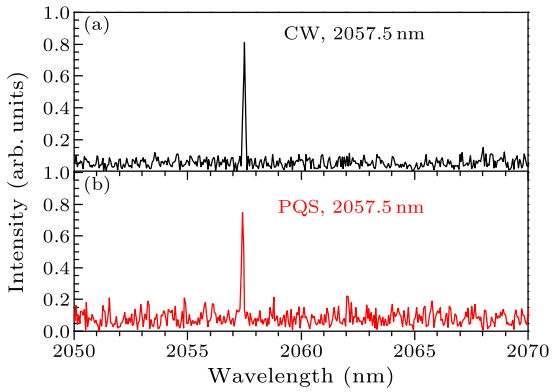


Fig. 3. Output spectra of cw and PQS Ho:$LuVO_4$ lasers.

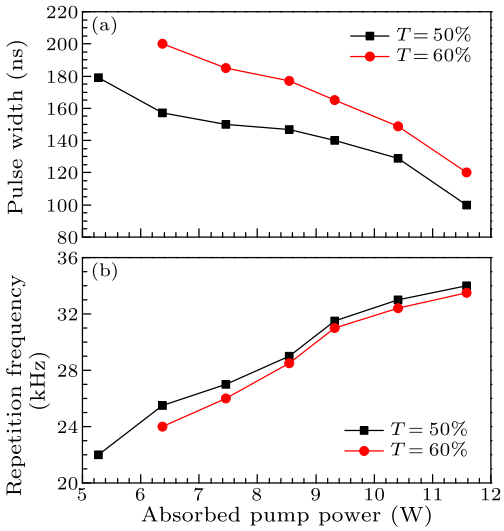


Fig. 4. The pulse width (a) and the repetition frequency (b) versus the absorbed pump power.

The laser pulse is recorded by a Lecroy digital oscilloscope (Wavesurfer 64 Xs, 2.5 G-samples/sec, 600 MHz bandwidth) with an InGaAs detector. Figure 4(a) shows the pulse width versus the absorbed pump power. The pulse width decreases from 179 ns to 100 ns and from 200 ns to 120 ns with the increase of the absorbed pump power corresponding to the output coupler $T = 50\%$ and 60%, respectively. Figure 4(b) shows the pulse repetition frequency versus the absorbed pump power. As can be seen, for $T = 50\%$ and $T = 60\%$, the pulse repetition frequency increases with the absorbed pump powers from 22 kHz to 34.2 kHz and from 24 kHz to 33.5 kHz. This is due to the fact that with the increase of the absorbed pump power, the intracavity gain coefficient is increased and the bleaching time of Cr^{2+}:ZnS SA is shortened, which increases the repetition frequency. In addition, we also find that with the increase of the output coupler transmittance, the pulse width increases and the repetition frequency decreases with the same absorbed pump power.

The reason is that with the increase of the output coupler transmittance, the cavity loss is increased, the cavity energy storage is reduced and the bleaching time of Cr^{2+}:ZnS SA becomes longer, thereby increasing the pulse width and reducing the repetition frequency. We can find that the pulse width and the pulse repetition frequency of Ho:$LuVO_4$ laser can be controlled by changing the absorbed pump power and the transmittance of the output coupler.

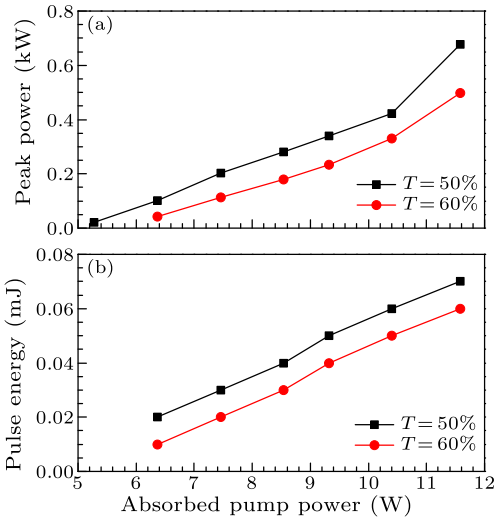


Fig. 5. The peak power (a) and the pulse energy (b) versus the absorbed pump power.

Figure 5 shows the peak power and the pulse energy versus the absorbed pump power. From Fig. 5(a), we can know that when the output coupler transmittances are 50% and 60%, the peak power changes from 0.02 kW to 0.67 kW and from 0.04 kW to 0.50 kW. In Fig. 5(b), the pulse energy changes from 0.02 mJ to 0.07 mJ and from 0.01 mJ to 0.06 mJ corresponding $T = 50\%$ and $T = 60\%$, respectively. From Fig. 5 we can draw the conclusion that both the peak power and the pulse energy increase with the absorbed pump power with the same output coupler transmittance. At the same time, both the peak power and the pulse energy decrease with the increase of the output coupler transmittance with the same absorbed pump power.

At the absorbed pump power of 11.6 W, the pulse train with the repetition frequency of 34.2 kHz and single-pulse profile with duration of 100 ns for $T = 50\%$ output coupler are shown in Fig. 6. It can be found that the output pulses always show good stability. The pulse duration is determined by the intracavity photon life, which is positively correlated with the cavity length and the inverse relationship with the cavity loss. To obtain a shorter pulse duration, we can shorten the length of the cavity and reduce the small signal transmission of the SA and the transmittance of the output coupler.

The maximum cw output power 2.7 W is obtained at $T = 50\%$. To determine the beam quality factor M^2 of the vertical direction, we route the Ho:$LuVO_4$ laser

radiation though an $f = 100$ mm focal length lens, and measure the $1/e^2$ beam radius along the propagation direction at cw output powers using a 90/10 knife-edge technique (shown in Fig. 7). Fitting the Gaussian beam standard expression to these data, we achieve the beam quality factor of $M_y^2 = 1.10$ in the vertical direction and $M_x^2 = 1.04$ in the horizontal direction. The beam intensity distribution is measured using a pyroelectric camera.

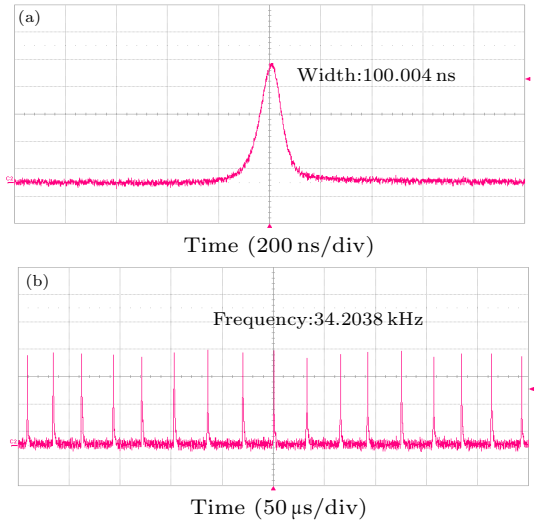


Fig. 6. (a) Typical oscilloscope trace of expanded shape of a single pulse. (b) A train of output pulses.

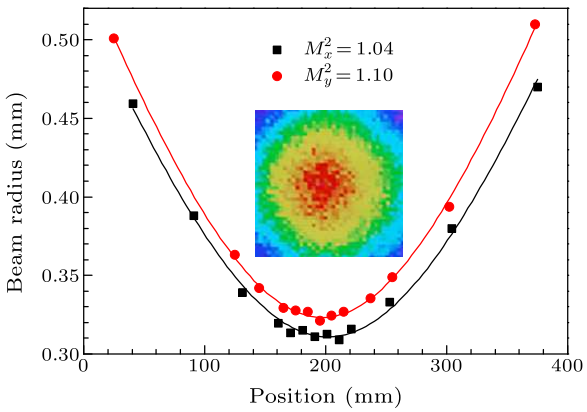


Fig. 7. The beam radius of the Ho:$LuVO_4$ laser. Inset: typical 2D beam profiles.

In conclusion, we have reported a PQS Ho:$LuVO_4$ laser by diode-pumped Tm:YAP lasers. To the best of our knowledge, it is the first PQS Ho:$LuVO_4$ laser with Cr^{2+}:ZnS as the SA. The experiment shows great potential of Ho:$LuVO_4$ PQS lasers in generating short pulses. With the output couplers $T = 50\%$ and 60%, the central wavelength of the laser output in both cw and PQS operations remains to be 2057.5 nm. In the PQS operation, with the absorbed pump power 11.6 W and the output coupler transmittance of 50%, the maximum average output power 2.3 W with the shortest pulse width 100 ns and the maximum pulse energy 0.07 mJ are obtained. When the output coupler transmittance is 60%, the average output power, peak power and pulse energy are lower than those of $T = 50\%$ with the same absorbed pump power. In the cw operation, the maximum output power 2.7 W is obtained corresponding to optical–optical conversion efficiency of 23.3% with $T = 50\%$. At this moment, the measured beam quality of $M_x^2 = 1.04$ and $M_y^2 = 1.1$ in both directions perpendicular to the axis of propagation.

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