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Diode-Pumped Quasi-Three-Level Passively Q-Switched Nd:GGG Laser with a Codoped Nd,Cr:YAG Saturable Absorber *

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We demonstrate the first quasi-three-level passively Q-switched Nd:GGG laser at 937 nm using a Nd,Cr:YAG crystal as the saturable absorber. The dependences of the average output power, the repetition rate and the pulse width on the incident pump power are obtained. A maximum average output power of 1.18 W with repetition rate of 35 kHz and pulse width of 45 ns is achieved at an incident pump power of 18.3 W. The corresponding optical-to-optical and slope efficiencies are 6% and 10%, respectively.

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Pulsed blue lasers have attracted a great deal of attention for various applications such as underwater communication and remote sensing. They can be efficiently obtained by frequency doubling Q-switched Nd-doped quasi-three-level ${}^4F_{3/2} \rightarrow {}^4I_{9/2}$ transition lasers around 0.9 µm.[1,2] However, the ${}^4F_{3/2} \rightarrow {}^4I_{9/2}$ laser transition is difficult to obtain due to its quasi-three-level properties such as very small stimulated emission cross section and serious re-absorption loss. As far as we know, quasi-three-level Q-switched lasers have been obtained mainly with laser materials such as Nd:YAG[3−5] or Nd,Cr:YAG,[6−8] and no report relating to Nd:GGG has been found. The Nd:GGG was first fabricated by Linares with the CZ method in 1964.[9] It has many advantages compared to Nd:YAG: for example, with the conventional method it can be grown with the higher Nd^{3+} ion without the considerable luminescence quenching due to its larger segregation coefficient (0.52) relative to that of Nd:YAG (0.2).[10] Nowadays, the Nd:GGG is known for its extensive use in solid state heat capacity lasers owing to its large size and high optical properties.[11,12] In 2007, our group successfully realized quasi-three-level operation at 937 nm.[13] In this Letter, we report the passive Q-switching operation on a quasi-three-level Nd:GGG with an Nd,Cr:YAG as the saturable absorber. In this experiment, the detailed laser performance of the Nd:GGG quasi-three-level passively Q-switched laser is investigated.

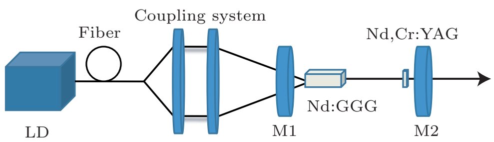

Fig. 1. Schematic diagram of the LD-pumped Nd:GGG passively Q-switched laser with a Nd,Cr:YAG as the saturable absorber.

A simple and compact linear resonator was used in our experiment. Figure 1 shows the sketch of the experimental setup. A high-brightness fiber-coupled cw laser diode (LD) with a central wavelength of approximately 805 nm was used for optical pumping. The maximum power of the diode was 30 W and the width of the diode emission spectrum was 3.5 nm (FWHM). The optical fiber had a diameter of 200 µm and a numerical aperture of 0.22. A 1:1 coupling system with a focal length of 25 mm was used to inject the pump laser into the Nd:GGG crystal with a size of $3 \times 3 \times 7\,mm^3$ and Nd^{3+} concentration of 0.5 at.%. The Nd,Cr:YAG saturable absorber with small signal transmission of 98% was cut at the dimensions of $\Phi 5 \times 1\,mm^3$. The Nd:GGG crystal and the Nd,Cr:YAG saturable absorber were both wrapped within indium foils and mounted in water-cooled copper blocks with a water temperature of 15°C. To reduce the cavity loss and to efficiently suppress the ${}^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition of Nd^{3+} ion, the Nd:GGG and the Nd,Cr:YAG saturable absorber were both highly transmission coated on two facets at 808 nm, 937 nm, 1064 nm and 1342 nm. A mirror M1 with curvature radius of 50 mm was highly reflectively coated at 937 nm and highly transmitting at 808 nm, 1064 nm and 1342 nm. M2 was a plane output coupling. In this experiment, two different plane output couplings were used. One had a transmission of 3.2% at 937 nm, the other 1.9% at 937 nm. The total length of the resonator was about 20 mm. The distance between M1 and the left surface of the Nd:GGG crystal was 2 mm. The results obtained with the ABCD matrix show that, closer to the output mirror, the laser beam spot size in the resonator was smaller. Thus in the experiment we tried to insert Nd,Cr:YAG crystal as close as possible to the output mirror, in order to easily realize the Q-switching operation according to

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the second threshold condition.[14] The waist radius of the pump light in the Nd:GGG crystal was about 110 µm. The waist radius inside the resonator was calculated according to the ABCD matrix theory with a thin lens in the middle of the laser crystal. Figure 2 shows the waist radius of the 937 nm oscillating laser at different positions inside the resonator when the focal length of the thermal lens changed from 18 mm to 128 mm. From Fig. 2, we can see that the waist radius of the 937 nm laser at the position of the M2 was about 40 µm, and the permissible dynamic range of the thermal focal length of our resonator was large. When the focal length of the thermal lens changed from 18 mm to 128 mm the resonator was in stable region. In this experiment, the Q-switched laser signal was detected by a fast photodiode detector with a rise time of less than 1 ns. An oscilloscope (Tektronix 500 MHz bandwidth and 500 MS/s) was used to monitor and to measure the Q-switched pulses.

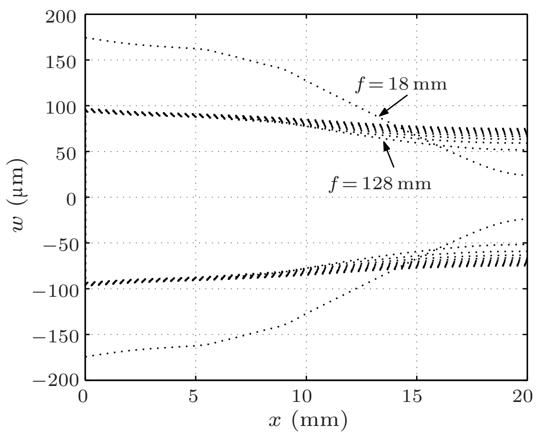

Fig. 2. Waist radius W (µm) of the 937 nm laser at different intracavity positions. We simulate the resonator with the focal length of the thermal lens from 18 to 128 mm. The origin of the coordinate axis in Fig. 2 corresponds to the position of input mirror M1 in Fig. 1 and x represents the different intracavity position in Fig. 1.

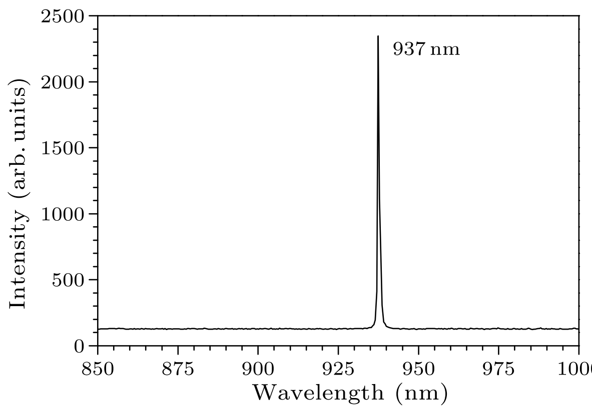

Fig. 3. Laser spectrum of the Nd:GGG passively Q-switched laser.

We measured the laser spectrum of the passively Q-switched laser and illustrate the result in Fig. 3, from which we can see that the peak emission wavelength was 937 nm and the full width at half maximum (FWHM) was smaller than 2 nm.

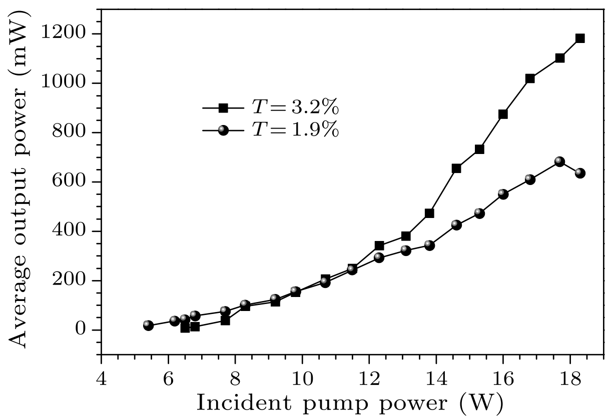

Fig. 4. Output power of the 937 nm pulsed laser versus the incident pump power for output coupling with $T = 3.2\%$ and $T = 1.9\%$, respectively.

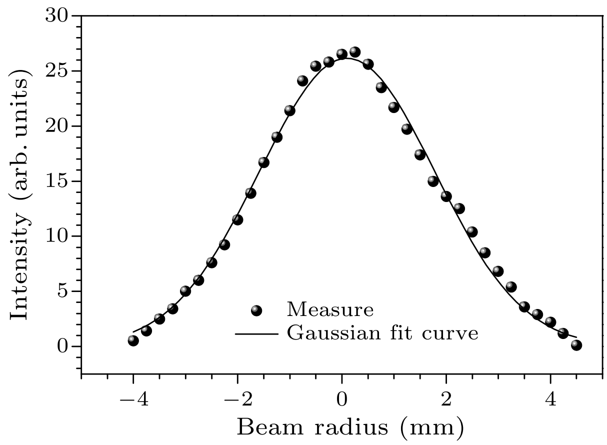

Fig. 5. Beam spatial profile of the 937 nm Q-switched laser at a distance of 50 cm from M2.

The average output powers of the passively Q-switched laser versus the incident pump power for two output couplings are shown in Fig. 4. It shows that the average output powers for both the output couplings were proportional to the incident pump power. The threshold pump power was 6.5 W and 5.4 W for output coupling with $T = 3.2\%$ and $T = 1.9\%$, respectively. A maximum output power of 1.18 W was obtained at a pump power of 18.3 W with a corresponding optical-optical efficiency of 6% and a slope efficiency of 10% using the output coupling with $T = 3.2\%$. For the output coupling with $T = 1.9\%$, the maximum output power of 635 mW was obtained with 17.7 W incident pump power. Beyond 17.7 W the output power tended to drop, which did not occur for the output coupling with $T = 3.2\%$. This may be caused by different thermal lens focal lengths at the same incident pump power. The thermal lens focal length of the Nd:GGG crystal was measured to be 21 mm with the plate-plate cavity method[15] under an incident pump power of 17.7 W. The central wavelength of the pump source shifted about 3 nm from the central wavelength (808 nm) of the absorption bands of the Nd:GGG crystal, which is unfavorable for the utilization of the incident pump power. We expect to obtain lower threshold pump power and higher output power with an appropriate pump source in future work. When the output power was 1.18 W the beam spatial profile of the 937 nm Q-switched laser at a distance of 50 cm from the M2 was measured using a small pinhole scanning method. The data and the Gaussian curve fitted result are shown in Fig. 5, from which we can see that the laser oscillated in the quasi-fundamental transverse mode. According to Fig. 5, the beam divergence was about 13 mrad.

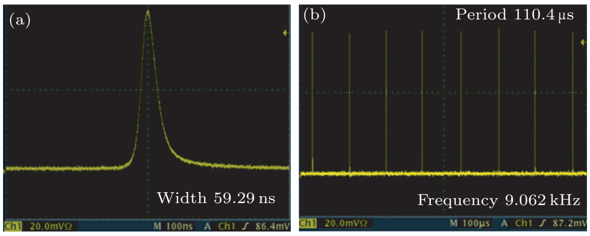

Fig. 6. (a) Typical temporal shape of single Q-switched pulse with a pulse width of 59 ns (b). Oscilloscope trace of the 937 nm Nd:GGG passively Q-switched laser, with a repetition rate of 9 kHz.

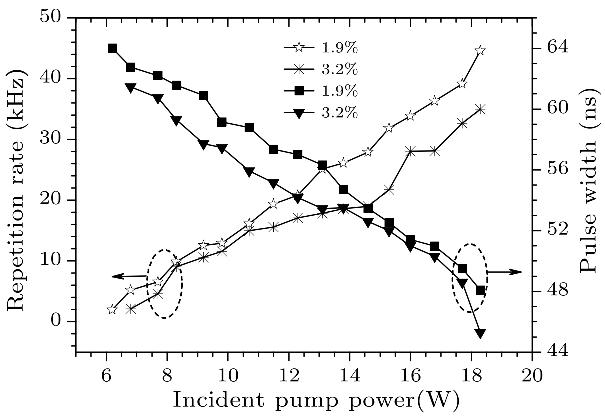

Fig. 7. Repetition rate and pulse width of the 937 nm pulsed laser versus the incident pump power.

Figure 6 shows the typical temporal shape of a single Q-switched pulse with a pulse width of 59 ns and the pulse train with a repetition rate of 9 kHz at the incident pump power of 8.3 W using an output coupling with $T = 3.2\%$. As shown in Fig. 6(b), the Q-switched pulse train was quite stable with a pulse amplitude and repetition rate jitter of less than 3%. The pulse amplitude and repetition rate jitter increase with incident pump power. The curves describing the repetition rate and pulse width of the passively Q-switched laser with incident pump power for two output couplings are shown in Fig. 7. We can see that the repetition rate increases from 2 kHz to 45 kHz while the pulse width decreases from 64 ns to 48 ns when the incident pump power increases from 6.2 W to 18.3 W for the output coupling with $T = 1.9\%$. The minimum pulse width of 45 ns was obtained by using the output coupling with $T = 3.2\%$. When the incident pump power increases from 6.8 W to 18.3 W with $T = 3.2\%$, the pulse width decreases from 61 ns to 45 ns and the repetition rate increases from 2 kHz to 35 kHz. It is clear that for the two output couplings with the increase of the incident pump power the repetition rate almost linearly increases while the pulse width almost linearly decreases. The lower the transmission of the output coupling used, the larger the pulse width and the higher the repetition rate were obtained at the same incident pump power. These results are in agreement with the basic theory of Q-switching[16] and similar results have been demonstrated experimentally by other groups.[17,18]

In conclusion, we have successfully demonstrated a passively Q-switched 937 nm Nd:GGG laser with a Nd,Cr:YAG as the saturable absorber. The dependences of the average output power, the repetition rate and the pulse width on the incident pump power are obtained. The maximum average output power of 1.18 W with a repetition rate of 35 kHz and a pulse width of 45 ns are obtained at an incident pump power of 18.3 W, with the corresponding optical-to-optical and slope efficiencies 6% and 10%, respectively.

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