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Diode-pumped passive Q-switched and mode-locked 946 nm Nd:YAG laser with a Nd, Cr:YAG saturable absorber

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Abstract

We report for the first time a diode-pumped simultaneous Q-switched and mode-locked 946 nm Nd:YAG laser with a diffusion bonded composite laser rod and a co-doped Nd, Cr:YAG as saturable absorber. The influence of the different initial transmission (T_0) of the saturable absorber on the Q-switched and mode-locked pulse was experimentally demonstrated. At an incident pump power of 16.5 W, the average output power of 600 mW with 42 kHz repetition rate and 570 ns pulse width of the Q-switched envelope was generated. Almost 100% modulation depth with 205 MHz repetition rate of the mode-locked pulse within the Q-switched envelope was achieved when the incident pump power was 15 W.

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Keywords: Diode-pumped lasers; Q-switching; Mode locking

1. Introduction

Diode-pumped passive Q-switched and mode-locked lasers have been widely applied in laser communication, remote sensing and non-linear optics due to the advantages of compactness and high efficiency. Cr^{4+}:YAG crystal is a perfect saturable absorber to generate the Q-switched and mode-locked pulses owing to its excellent optical, thermal and mechanical properties [1,2]. Co-doped Nd, Cr:YAG crystal is another widely used saturable absorber [3,4]. When the intracavity intensity is low, the transition in the Cr^{4+} ion takes place between the ground state and the first excited state. In this case, the crystal acts only as a saturable

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absorber for Q-switching. However, when the intracavity intensity is very high, the populations of the ground state are fast excited to the first excited state and the strong excited state absorption in the Cr^{4+} ion may result in its saturation, which leads to mode-locking [5–7]. Some studies about passive Q-switched and mode-locked laser operating at 1064 nm using Nd, Cr:YAG as saturable absorber have been reported [8–11]. Passive Q-switched and mode-locked 946 nm laser has attracted more attention because of its potential to generate high-power and high-repetition-rate blue laser through frequency doubling. However, simultaneous Q-switched and mode-locked laser operating at 946 nm has not been reported owing to the reabsorption loss of the quasi-three level system and the small stimulated emission cross-section compared with that of the 1064 nm laser. In order to obtain sufficient intracavity intensity to realize the 946 nm Q-switched and mode-locked operation, high pump power must be cast to the laser crystal. As a result, the laser crystal will be loaded with enormous heat. To minimize the heat effect effectively, we employ a diffusion bonded composite laser rod instead of the conventional crystal. The composite laser rod is reliable for heat transfer from both faces of the Nd:YAG crystal through two undoped YAG caps when the Nd:YAG crystal is operating at high pump power. This kind of laser crystal also increases its damage threshold. According to Yang et al. [9,10], a co-doped Nd, Cr:YAG has lower saturation intensity in the Q-switched and mode-locked 1064 nm laser. So we selected the crystal of Nd,Cr:YAG as saturable absorber in our experiment. In this letter we report, for the first time to our knowledge, a Q-switched mode-locked 946 nm Nd:YAG laser through optimizing the laser crystal, saturable absorber and the cavity. We demonstrate experimentally the effect of T_0 of the saturable absorber on the passive Q-switched and mode-locked pulse. As much as 600 mW of average output power of simultaneous Q-switched and mode-locked pulses were generated. The Q-switched envelope has 42 kHz repetition rate and 570-ns pulse width. Almost 100% modulation depth with 205 MHz repetition rate of the mode-locked pulse in the Q-switched envelope was obtained.

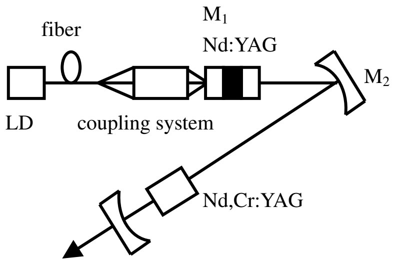

Fig. 1. Schematic of a passive Q-switched and mode-locked 946 nm Nd:YAG laser.

2. Experimental setup

The experimental setup is shown in Fig. 1. A three-mirror folded cavity was designed to allow mode matching with the pump beam and to provide the proper spot size in the saturable absorber. The pump source was a 25 W/200-μm fiber-coupled diode laser with a numerical aperture of 0.22. The 808-nm pump light from a fiber was coupled into a diffusion-bonded Nd:YAG (3 mm YAG, 3 mm 1.0 at.% Nd:YAG, and 3 mm YAG). The pump facet of the laser rod was coated for high transmission (HT) at 808 nm, high reflection (HR) at 946 nm, while HT at 1064 nm and 1320 nm was specified to suppress parasitic oscillation at these transitions. The other side of the rod was coated with antireflection (AR) at 946, 1064 and 1320 nm. The saturable absorber was a co-doped Nd, Cr:YAG crystal, where both sides of the crystal were AR coated for 946 nm in order to reduce the loss of the laser cavity. The laser rod and the saturable absorber were both cooled directly with flowing water ($T = 15.2$ °C). The folding mirror M_2 was coated for HR at 946 nm. The output coupler was a concave mirror which has definite transmission at 946 nm. The Q-switched and mode-locked pulse temporal behavior was recorded by a digital oscilloscope (Tektronix 500 MHz bandwidth and 500 MS/s) and a fast photodiode with a rising time of less than 1 ns.

3. Experimental results and discussions

First, we investigated the relationship between different T_0 of the saturable absorbers and the

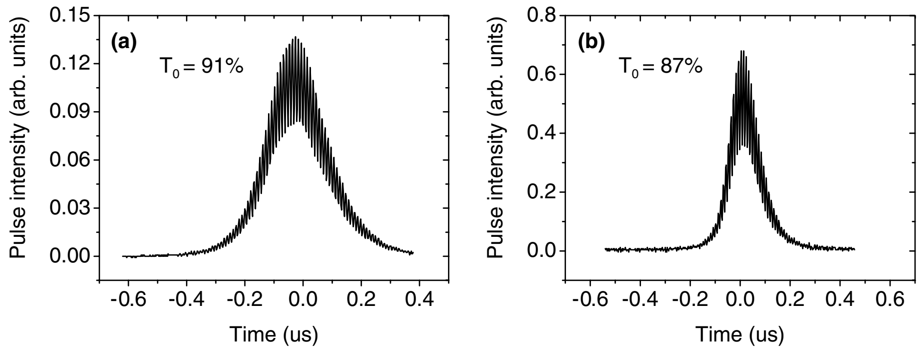

Fig. 2. Temporal profiles of the Q-switched and mode-locked laser pulses using different T_0 of the saturable absorbers when the incident pump power was 5 W.

passive Q-switched and mode-locked pulse with a cavity length of 36.3 cm. In the experiment, the folding mirror M_2 had a curvature radius of 150 mm. The output coupler had 5% transmission at 946 nm with 50 mm radius of curvature. Fig. 2 shows the Q-switched and mode-locked pulses using different T_0 of the saturable absorbers when the incident pump power is 5 W. For the Nd,Cr:YAG of $T_0 = 91\%$, the Q-switched pulse width and the mode-locked modulation depth are 240 ns and 39%, respectively. While for the Nd,Cr:YAG of $T_0 = 87\%$, the Q-switched pulse width and the mode-locked modulation depth are 134 ns and 48%, respectively. From Fig. 2 we conclude that the saturable absorber with lower T_0 can not only shorten the width of the Q-switched envelope but also increase the modulation depth of the mode-locked pulse in the Q-switched envelope. Similar result was also observed at 1064 nm laser in the reference of [12].

In order to optimize the cavity further, the folding mirror M_2 was replaced by a mirror with 300 mm radius of curvature and the output coupler was replaced by a mirror which had 4% transmission at 946 nm with a curvature radius of 150 mm. The cavity length was 72.6 cm. The spot radius of the pump light in the Nd:YAG crystal was about 120 μm. The spot radius of the oscillating light in the laser crystal was calculated to be about 110 μm by using ABCD matrix and considering the thermal-lensing effect. The threshold of the Q-switched and mode-locked pulse was only 3 W owing to the efficient mode match between the pump light and the oscillating light. Fig. 3 presents the average output power as a function of the incident pump power. At 16.5-W incident pump power, the average output power was as much as 600 mW with a slope efficiency of 4.4%. The repe-

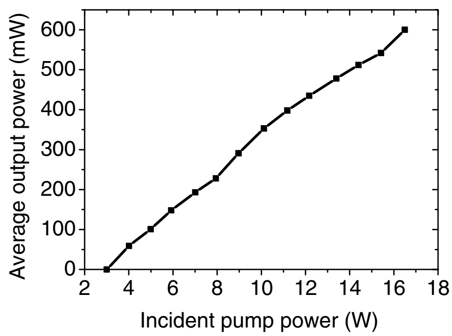

Fig. 3. The average output power as a function of the incident pump power.

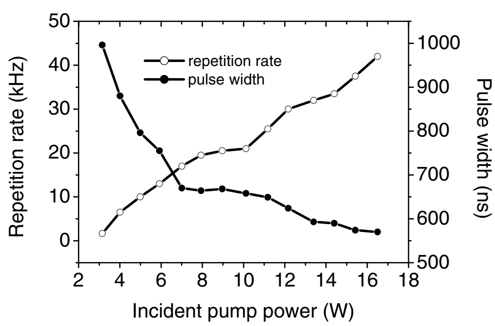

Fig. 4. The repetition rate and pulse width of the Q-switched envelope as a function of the incident pump power.

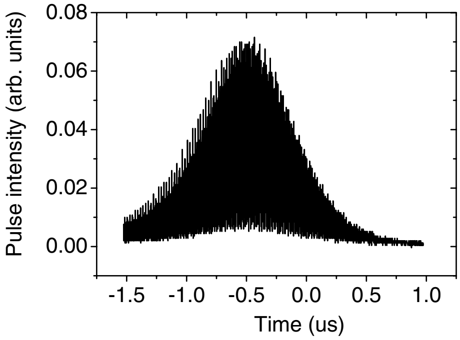

Fig. 5. Temporal profile of the Q-switched and mode-locked laser pulses when the cavity length was 72.6 cm.

tition rate and pulse width of the Q-switched envelope as a function of the incident pump power are shown in Fig. 4. The repetition rate of the Q-switched pulse increases almost linearly with the incident pump power, whereas the pulse width decreases with the incident pump power. With an incident pump power of 16.5 W, the pulse repetition rate is 42 kHz with pulse width of 570 ns and the Q-switched pulse energy is 14.3 μJ. The energy of a single mode-locked pulse near the maximum of the Q-switched envelope is 0.12 μJ. Fig. 5 presents a almost 100% modulation depth when the incident pump power is 15 W. The mode-locked pulse interval within the Q-switched envelope is 4.87 ns, corresponding to a repetition rate of 205 MHz, which is in good agreement with the theoretical calculation.

4. Conclusion

In conclusion, we have demonstrated a diode-pumped passive Q-switched and mode-locked 946 nm Nd:YAG laser with a composite laser rod and a saturable absorber of Nd, Cr:YAG crystal. It is found that the saturable absorber with lower T_0 can not only shorten the width of the Q-switched envelope but also increase the modulation depth of the mode-locked pulse in the Q-switched envelope. At an incident pump power of 16.5 W, 600 mW of average output power with 42 kHz repetition rate and 570 ns pulse width of the Q-switched envelope was achieved. The Q-switched pulse energy is 14.3 μJ. The energy of a single mode-locked pulse near the maximum of the Q-switched envelope is 0.12 μJ. For a cavity length of 72.6 cm almost 100% modulation depth with 205 MHz repetition rate of the mode-locked pulse in the Q-switched envelope was obtained with an incident pump power of 15 W.

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