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Q-switched and mode-locked diode-pumped Nd:YVO_4 laser with an intracavity composite semiconductor saturable absorber

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Abstract

We have demonstrated a passively Q-switched and mode-locked Nd:YVO_4 laser with an intracavity composite semiconductor saturable absorber (ICSSA). Stable Q-switched and mode-locked pulses with Q-switched envelope pulse duration of 180 ns and pulse repetition rate of 72 KHz have been obtained. The maximum average output power was 1.45 W at 8 W incident pump power. The repetition rate of the mode-locked pulses inside the Q-switched envelope was 154 MHz. Experimental results revealed that this ICSSA was suitable for Q-switched and mode-locked solid-state lasers.

Keywords: Q-switched mode-locking; Composite saturable absorber; Nd:YVO_4 laser

1. Introduction

Simultaneous Q-switching and mode-locking (QML), one of the oldest modes of laser operation, has became to be one of the attractive topics of laser physics in recent years. QML provides a simple way to increase the pulse peak power by orders of magnitude in comparison to the continuous wave (CW) mode-locking regime. High-peak power lasers are required for various applications like nonlinear frequency conversion, mid-IR remote sensing, ranging and so on. So far, a variety of methods for QML has been investigated, such as Cr:YAG, LiF:F_2, GaAs wafer, V:YAG, nonlinear mirror and so on [1–7]. In this experiment, we designed a new simple and robust intracavity composite semiconductor absorber with LT $In_{0.25}Ga_{0.75}As$ [8,9] and pure GaAs [10] for the Q-switched and mode-locked laser and achieved stable QML in the Nd:YVO_4 laser with the absorber.

In recent years, though many new crystals have been used for diode-pumped solid-state lasers [11–15], the old crystal Nd:YVO_4 still has been identified as an excellent material especially for diode-pumped mode-locked solid-state lasers. Nd:YVO_4 has many advantages including a large emission cross-section, a large absorption coefficient, a wide absorption bandwidth and a polarized output.

In this experiment, we firstly presented QML in an Nd:YVO_4 laser by using a new ICSSA as the saturable absorber. Stable QML pulse train was achieved. The highest average output power was 1.67 W with a 70% reflectivity output coupler. Narrow Q-switched envelope pulse duration of 180 ns was generated with an 80% reflectivity output coupler and the repetition rate of the Q-switched envelope was 72 KHz. The repetition rate of the mode-locked pulse was 154 MHz.

2. The intracavity composite semiconductor saturable absorber (ICSSA)

The composite semiconductor absorber is composed of two absorbers. One is the semi-insulating GaAs substrate itself (the pure GaAs); the other is the deposition layers [a GaAs (15 nm) /$In_{0.25}Ga_{0.75}As$ (10 nm)/GaAs (15 nm)

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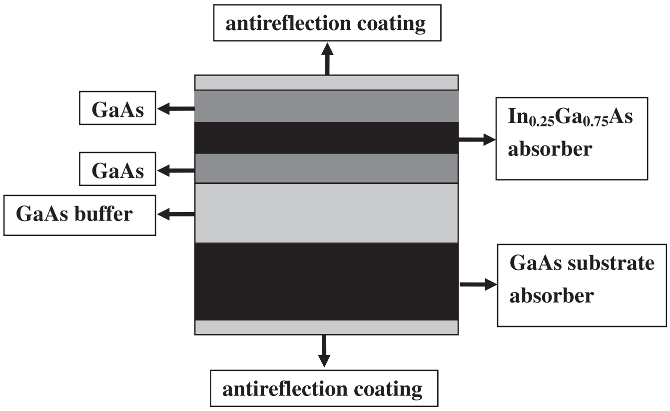

Fig. 1. The structure of the intracavity composite semiconductor saturable absorber.

single-quantum-well], which is grown at low temperature and is similar to semiconductor saturable absorber mirror (SESAM) for mode locking. The initial transmission of the ICSSA is about 90%. The structure of the absorber is shown in Fig. 1.

The composite semiconductor absorber was fabricated mainly by the Metal Organic Chemical Vapor Deposition (MOCVD) technique. First, a 500 nm GaAs buffer layer was deposited on the semi-insulating GaAs substrate with the thickness of 500 μm. Second, a single-quantum-well composed of GaAs (15 nm) /$In_{0.25}Ga_{0.75}As$(10 nm)/ GaAs(15 nm) was grown on the buffer layer at low temperature of 550 °C (for MOCVD, the normal temperature is from 600 to 750 °C). Third, the wafer was polished from the other side of the wafer in order to decrease nonsaturable loss and polished. Finally, both sides of the wafer were antireflection coated.

The principle for undoped (or pure) semi-insulating GaAs as a Q-switching absorber was studied by Kajava [16]. Differently, LT GaAs/$In_{0.25}Ga_{0.75}As$/GaAs absorber has some characteristics similar to those of SESAM. Carriers in $In_{0.25}Ga_{0.75}As$ excited from valence band to conductor band and the absorption for 1.06 μm laser is as 10^4 times as that in LT GaAs or pure GaAs wafer. In addition, LT $In_{0.25}Ga_{0.75}As$ as well as LT GaAs can act as rapid recombination center for carriers as pure GaAs wafer. The density of AsGa in LT GaAs ($\sim 10^{19}\,cm^{-3}$) is much higher than that in pure GaAs wafer (generally less than $10^{15}\,cm^{-3}$), Therefore, the number of AsGa traps in several tens of nanometer LT GaAs or LT $In_{0.25}Ga_{0.75}As$ can compare to that in several hundred micrometer pure GaAs wafer, which is relating to recovery time and saturable loss.

3. Experimental setup and results

The cavity configuration is shown in Fig. 2. The Nd^{3+} concentration of the laser crystal was 0.5 at%, and its length was 5 mm. The laser crystal was wrapped with indium foil and mounted in a copper block cooled by a thermo-electric cooler. One side of the laser crystal was coated antireflection for 808 nm ($T > 98\%$) pump wavelength and high reflection ($R > 99.8\%$) for the 1064 nm lasing radiation, the other side was coated antireflection for 1064 nm. The pump source was 8 W fiber-coupled laser diode with a core diameter of 0.4 mm and a numerical aperture of 0.22. The fiber output was focused into the laser crystal and the pump spot radii was about 200 μm. The resonator consisted of two highly reflective (at 1064 nm) mirrors, M1 and M2; one partially reflective (PR) mirror, OC; a laser crystal; and an ICSSA. OC is a flat mirror; the radii of curvature for M1 and M2 are 500 and 100 mm, respectively. Considering the thermal lens effect of the laser crystal, the cavity was designed to easily allow mode matching with the pump beam and to provide the proper spot size in the ICSSA. The total cavity length was about 975 mm. M1 and M2 were separated by about 630 mm, the crystal and M1 were separated by about 290 mm. The ICSSA was placed as near as possible to the output coupler. The mode radii in the crystal was about 170 μm and the mode radii on the ICSSA was approximately 30 μm. The ICSSA was simply mounted on a copper heat sink, but no active cooling was applied.

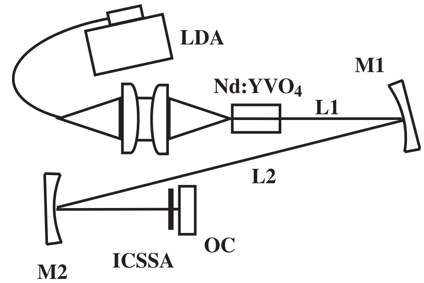

Fig. 2. Configuration of the QML $Nd:YVO_4$ laser with an ICSSA.

In the first part of the experiment, the QML performance was studied by using an 80% reflectivity (at 1064 nm) mirror as the output coupler. To provide the baseline for evaluating the Q-switched mode-locking efficiency, we studied the CW (without the ICSSA) performance of the present laser firstly. In the CW regime, the laser threshold was about 1 W and the output power reached 3.1 W at 8 W incident pump. In Fig. 3, the laser output power was plotted as a function of incident pump power. With the ICSSA, the laser began to operate when the pump power was 2 W and the maximum output power was 1.45 W at 8 W pump power. The behavior of laser average output power as a function of the incident pump power was investigated as shown in Fig. 3. The low threshold indicated that the ICSSA did not induce significant nonsaturable losses. The output power was limited by the available pump power. The temporal behavior of laser pulses was recorded by a fast-response InGaAs photodiode with a time resolution of 0.5 ns and a LeCroy oscilloscope (9361C). Near oscillation threshold the output was effectively CW; slightly increasing the pump power initiated a QML state; however, the pulse was not stable.

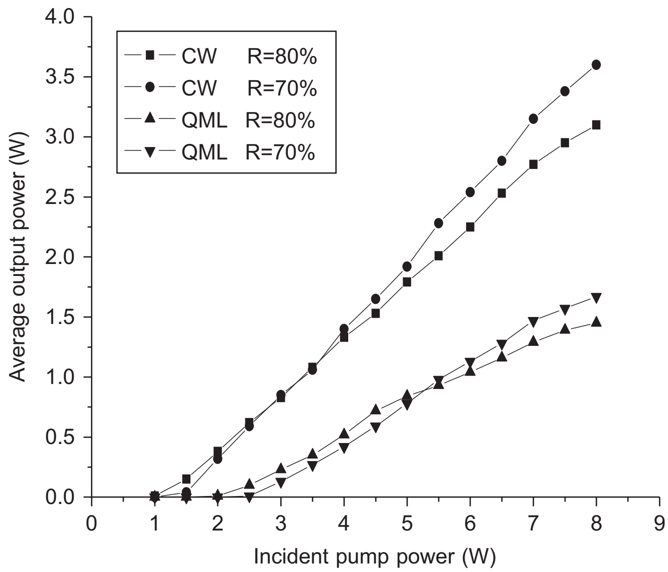

Fig. 3. The average output power as a function of the incident pump power with two different reflectivity output couplers.

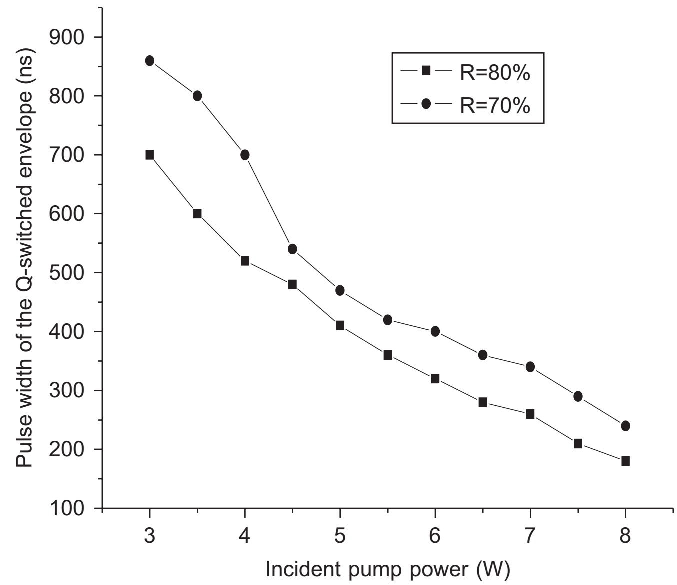

Fig. 4. The pulse width of the Q-switched envelope as a function of the incident pump power with two different reflectivity output couplers.

At the pump power of 3.5 W, the laser exhibited stable QML behavior. The repetition rate of the Q-switched envelope increased from 35 to 75 KHz as the incident pump power increased from 3 to 6 W, while decreased from 75 to 72 KHz as the incident pump power increased from 6 to 8 W. The pulse width of the Q-switched envelope decreased from 700 to 180 ns along with the increased incident pump power. The dependences of the pulse width and the repetition rate on the incident pump power were shown in Figs. 4 and 5 respectively. The depth of the mode locking also increased with the increased incident pump power, at 8 W incident pump power the depth was almost 100%. The QML pulses in different time division were shown in Fig. 6. The pulse duration was not accurately depicted in Fig. 6(c) because of the low bandwidth (300 MHz) of the oscilloscope and the low time resolution of the photodiode (0.5 ns).

In the second part of the experiment, a 70% reflectivity (at 1064 nm) mirror was used as the output coupler. In the CW regime, the laser threshold was about 1.2 W and the output power reached 3.6 W at 8 W incident pump. In Fig. 3, the laser output power was plotted as a function of incident pump power. With the ICSSA, the laser began to operate when the pump power was 2.5 W and the maximum output power was 1.67 W at 8 W pump power. The behavior of laser average output power as a function of the incident pump power was investigated as shown in Fig. 3. At the pump power of 4.6 W, the laser exhibited stable QML behavior. The repetition rate of the Q-switched envelope increased from 48 to 105 KHz as the incident pump power increased from 3 to 6.5 W, while decreased from 105 to 92 KHz as the incident pump power increased from 6.5 to 8 W. The pulse width of the Q-switched envelope decreased from 860 to 240 ns along with the increased incident pump power. The dependences of the pulse width and the repetition rate on the incident pump power were shown in Figs. 4 and 5, respectively. The depth of the mode locking also increased with the increased incident pump power, at 8 W incident pump power the depth was about 80%.

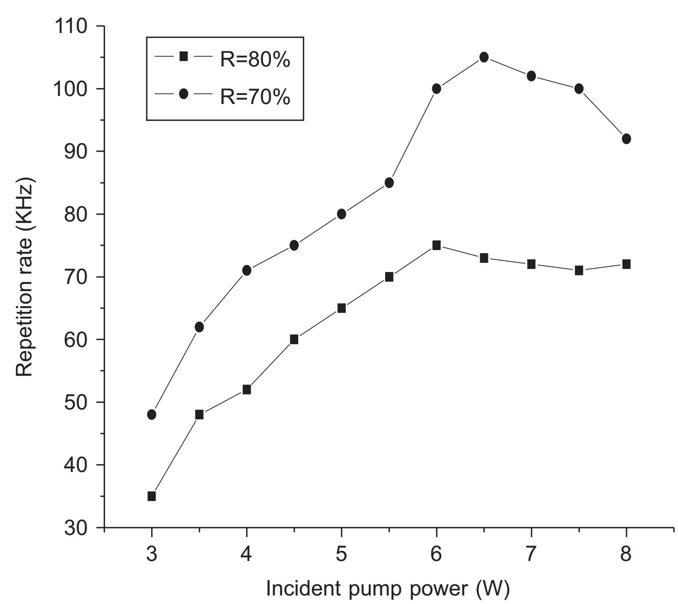

Fig. 5. The repetition rate as a function of the incident pump power with two different reflectivity output couplers.

From the experimental results, we know that the higher the reflectivity of the output coupler, the lower the repetition rate at the same incident pump power and the higher the reflectivity, the shorter the pulse width. The optic-to-optic conversion efficiency with the 70% reflectivity coupler was higher than that of the 80% reflectivity

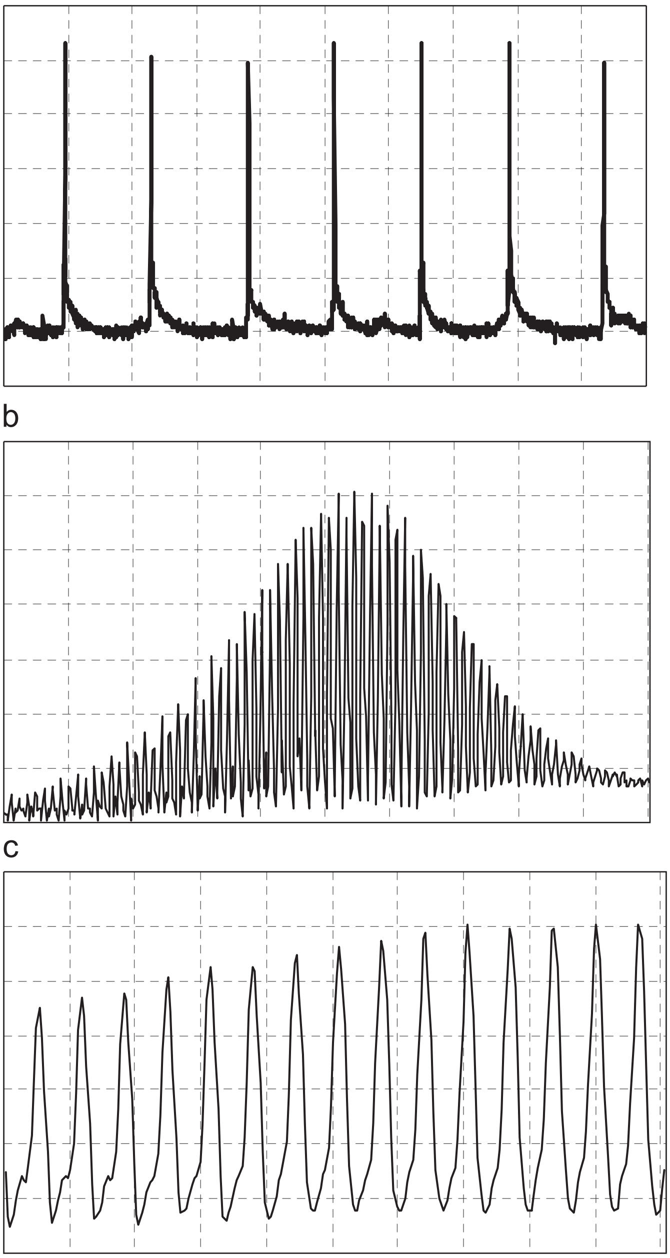

Fig. 6. The QML pulses in different time divisions: (a) the QML pulse train with repetition rate of 72 KHz (10 μs/div), (b) the single QML pulse with the envelope pulse width of 180 ns (50 ns/div) and (c) the mode-locked pulse train with the repetition rate of 154 MHz (10 ns/div).

coupler. But the threshold of stable QML (4.6 W) for the 70% reflectivity coupler was too high, and the depth of the mode locking did not reach 100%. Especially, the pulse-to-pulse fluctuation of the 70% reflectivity coupler was higher than that of the 80% reflectivity coupler. So, we thought that the 80% reflectivity coupler was the better choice for this laser.

4. Conclusion

In this experiment, we firstly investigated the performance of a new ICSSA in a passively Q-switched and mode-locked $Nd:YVO_4$ laser. To optimize the laser output, we selected two output couplers and from the experimental results we considered that the 80% reflectivity output coupler was better for this laser. With the 80% reflectivity output coupler, a maximum average output power of 1.45 W was obtained at 8 W incident pump power. The repetition rates of the Q-switched envelope pulse and the mode-locked pulse were 72 KHz and 154 MHz, respectively. The pulse width of the Q-switched envelope was about 180 ns. Experimental results indicated that this absorber was suitable for Q-switched and mode-locked solid-state lasers.

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