High-repetition rate Q-switched $Nd:YVO_4$ laser with a composite semiconductor absorber

Yong-Gang Wang, Xiao-Yu Ma, Ji-Ying Peng, Hui-Ming Tan, and Long-Sheng Qian

A diode-pumped $Nd:YVO_4$ laser passively Q switched by a semiconductor absorber is demonstrated. The Q-switched operation of the laser has an average output power of 135 mW with a 1.6 W incident pump power. The minimum pulse width is measured to be about 8.3 ns with a repetition rate of 2 MHz. To our knowledge, this is the first demonstration of a solid-state laser passively Q-switched by such a composite semiconductor absorber. © 2006 Optical Society of America

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1. Introduction

Q switching of diode-pumped lasers is an effective technique for generating pulses of nanosecond duration. Q-switched diode-pumped lasers have been realized actively, with an electro-optic modulator, or passively, by using the self-Q-switching properties of Cr-doped solid-state lasers.[1,2] However, Cr^{4+}:YAG crystal parameters such as recovery time and modulation depth cannot be modulated freely, which limits its application as an absorber. In 1999[3] $Nd:YVO_4$ passively Q switched with a semiconductor saturable absorption mirror (SESAM) was demonstrated, and a pulse duration as short as 37 ps was demonstrated. Pure GaAs was first used for passive Q switching by Kajava and Gaeta.[4] In their experiment the pulse duration was as short as 3 ns. In mode-locking operation, the passively Q-switched, mode-locked laser functions when the pump power is lower than the threshold of continuous-wave mode locking. The width of the Q-switching envelope is generally at the level of several hundred nanoseconds or several microseconds. In 2001 Chen *et al.*[5] demonstrated a Q-switched, self-mode-locked $Nd:YVO_4$ laser with a $LiF:F_2^-$ saturable absorber. The Q-switched pulse has a repetition rate of 260 kHz and pulse duration of approximately 250 ns. In 2004, Villafana *et al.*[6] analyzed the characteristics of a passive Q-switched $Nd:YVO_4$ laser with a $LiF:F_2^-$ saturable absorber. In 2005, Pan *et al.*[7] removed the minor pulses inside the Q-switching envelope by frequency selection technology and obtained pure Q-switching with a duration of 150 ns and a repetition rate of 76.3 kHz. In fact, pure Q switching could be observed without frequency selection technology when mode locking was limited in the cavity. To obtain much shorter pulses, the thickness of the SESAM's absorption layer should be increased to several tens of times that of the normal SESAM for passive mode-locking; the recovery time should be increased, too, which would introduce some difficulties in manufacturing and would increase the insertion loss of the device.

We demonstrate that a novel composite semiconductor absorber that is composed of low-temperature (LT) $GaAs/In_{0.25}Ga_{0.75}As/GaAs$ and pure GaAs can be used for passive Q switching a $Nd:YVO_4$ laser. A similar composite semiconductor absorber, as well as a coupler, has been used for mode locking.[8,9] Our laser system produces 8.3 ns pulses with energies up to 62.5 nJ. In addition, the pulse repetition rate is as high as 2 MHz. To the best of our knowledge, this is much higher than that of existing passively Q-switched lasers with an absorber such as Cr^{4+}:YAG, SESAM, and pure GaAs. Such a high-repetition-rate Q-switching pulse laser may be useful for rapid range finding or remote sensing.

2. Experiment

The composite semiconductor absorber is fabricated mainly by the metal-organic chemical-vapor deposi-

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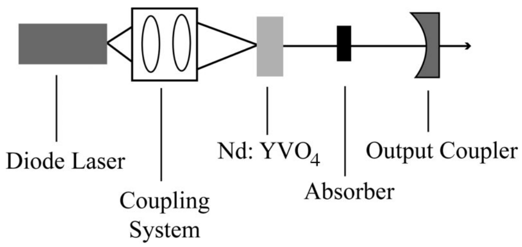

Fig. 1. Schematic of the laser.

tion (MOCVD) technique. First, a 500 nm GaAs buffer layer was deposited on the semi-insulating GaAs substrate with a 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 the LT of 550 °C. (For MOCVD the normal temperature is from 600 °C to 750 °C.) Third, the wafer was thinned to be about 100 μm from side to side to decrease nonsaturable loss, and it was polished. Finally, both sides of the wafer were antireflection coated.

To make a comparison in our experiment, we used both a composite semiconductor absorber and Cr^{4+}:YAG with transmissions of 60% and 80% as the absorber for the laser. Figure 1 shows our laser setup. By using a 2 W 808 nm laser diode with a 100 μm stripe size and an optical coupling system, we were able to achieve a small pump spot in the $Nd:YVO_4$ crystal while maintaining a compact pump setup. To tune the pump wavelength for maximum absorption by the gain medium, a semiconductor cooling plate was used to control the temperature of the diode. The gain medium was *a*-cut $Nd:YVO_4$ crystal with 1.0 at. % Nd doping, and the dimensions were 3 mm × 3 mm in surface aperture and 1.15 mm in length. The pump surface of the $Nd:YVO_4$ crystal was dielectrically coated to give a film of high reflectivity at a 1064 nm laser wavelength and high transmission at an 808 nm pump wavelength. The other face of the crystal was coated with a high-transmission film at 1064 nm. To alleviate the thermal load, the crystal was attached to a copper block and cooled by semiconductor cooling plates. The output mirror with a curvature radius of 100 mm has a transmission rate of 5% at 1064 nm. The total cavity length is about 12 mm.

3. Results and Discussion

The *Q*-switching pulse train was monitored by a fast-response photodiode and a Tektronix digital oscilloscope (TDS3052). Figure 2 shows the *Q*-switching pulses generated from a laser system *Q* switched with the composite semiconductor absorber and with Cr^{4+}:YAG with transmissions of 60% and 80% when the pump power is 1.6 W. From the diagram we know that the *Q*-switching pulse obtained with the composite semiconductor has a shorter duration (8.3 ns) than that obtained with the Cr^{4+}:YAG absorber (11.7 or 16.1 ns) and a higher repetition rate (2 MHz) than that with the Cr^{4+}:YAG absorber (65 kHz or 420 kHz).

A nearly linear increase in pulse repetition-rate from 400 kHz to 2 MHz (for the composite semiconductor absorber), 80–420 kHz (for T = 80% Cr^{4+}:YAG absorber) and 12–65 kHz (for the T = 60% Cr^{4+}:YAG absorber) as a function of pump power can be observed in Fig. 3. Figure 4 shows the relationship between the average output power and the pump power. Under the maximum pump power of 1.6 W, the output power from the laser with a composite semiconductor absorber is 135 mW, which is between that of the laser with T = 60% Cr^{4+}:YAG (182 mW) and T = 80% Cr^{4+}:YAG (75 mW). Similarly, the slope efficiencies satisfy the same relationship. Accordingly, they are 10.3%, 15.1% and 7.5%, respectively.

The pulse repetition rate obtained from the *Q*-switched laser with the composite semiconductor absorber is much higher than that obtained from the laser with the Cr^{4+}:YAG absorber in our experiment, which is related to the fact that the composite semiconductor absorber is composed of two absorbers. One is the semi-insulating GaAs substrate itself (the so-called pure GaAs in Refs. 2 and 4); the other is the deposition layers (a single quantum well composed of GaAs (15 nm)/$In_{0.25}Ga_{0.75}As$ (10 nm)/GaAs (15 nm), which is grown at low temperature) and is similar to a SESAM for mode locking.

The principle for using undoped (or pure) semi-insulating GaAs as a *Q*-switching absorber has been demonstated.[10] In contrast, the LT GaAs/$In_{0.25}Ga_{0.75}As$/GaAs absorber has some characteristics similar to those of a SESAM. Carriers in $In_{0.25}Ga_{0.75}As$ are excited from valence band to conductor band, and the absorption for a 1.06 μm laser is 10^4 times that in a LT GaAs or a pure GaAs wafer. In addition, LT $In_{0.25}Ga_{0.75}As$ as well as LT GaAs can act as a rapid recombination center for carriers, as can a pure GaAs wafer. The density of As_{Ga} in LT GaAs ($\sim 10^{19}$ cm^{-3}) is much higher than that in a pure GaAs wafer (generally less than $10^{15} cm^{-3}$). Therefore the number of As_{Ga} traps in several tens of nanometers of LT GaAs or LT $In_{0.25}Ga_{0.75}As$ can compare with that in several hundred micrometers of pure GaAs wafer, which is related to recovery time and saturable loss. LT GaAs/$In_{0.25}Ga_{0.75}As$/GaAs, besides acting as a coupler, can act as an absorber for mode locking.[8,9] We believe that the additional pure GaAs wafer does not play a major role in mode locking in these experiments. However, in this paper, *Q*-switching pulses with short durations and high repetition rates were observed when the laser cavity and pump power did not satisfy the conditions for mode locking. We believe that both absorbers play an important role in the *Q*-switching stage.

4. Summary

A diode-pumped $Nd:YVO_4$ laser operated under passively semiconductor absorber *Q*-switched conditions has been demonstrated. The minimum pulse width

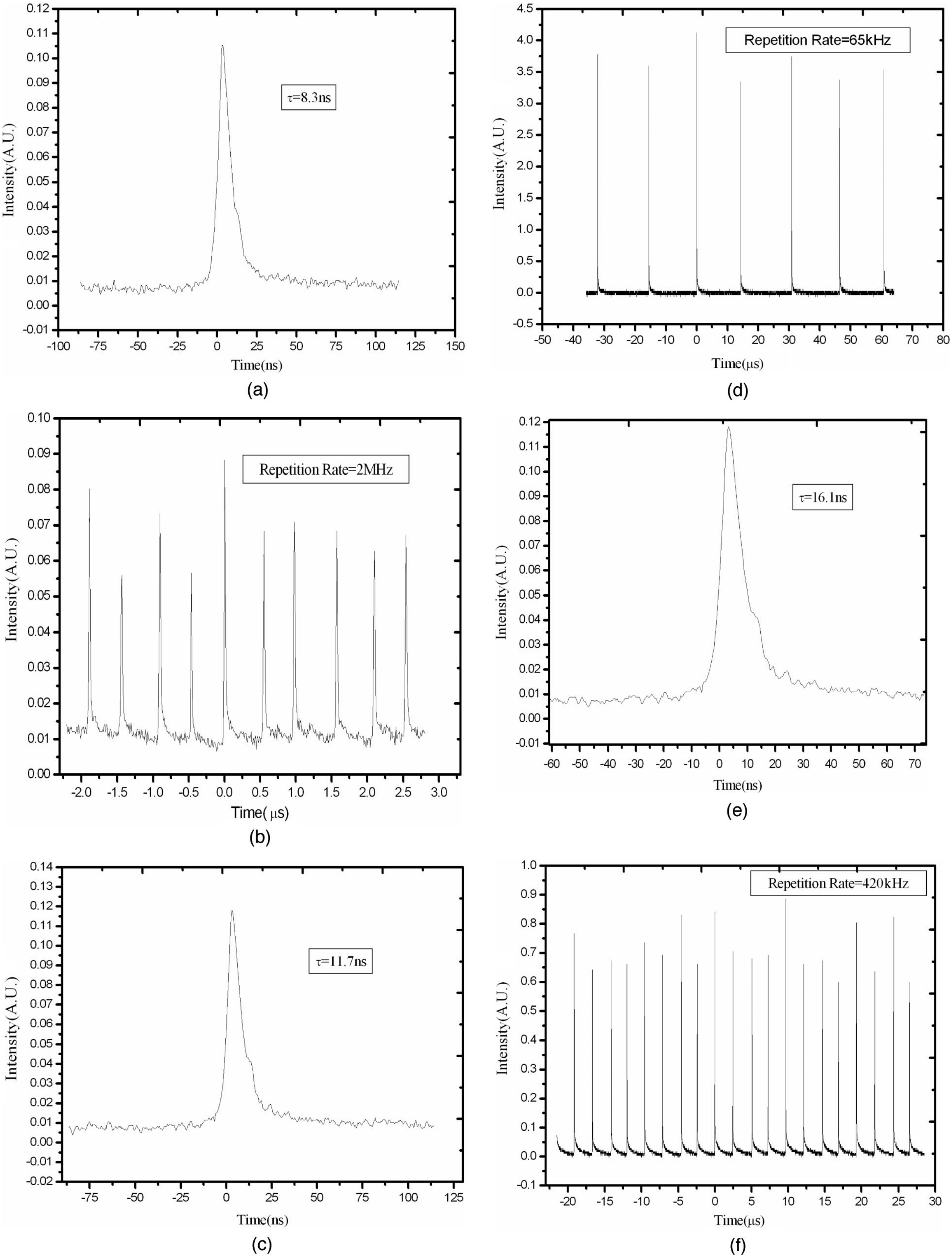

Fig. 2. Pulse train of the Q-switched Nd:YVO_4 laser with a pump power of 1.6 W. (a) Composite semiconductor absorber (FWHM of 8.3 ns); (b) composite semiconductor absorber (repetition rate of 2 MHz); (c) T = 60% Cr^{4+}:YAG (FWHM of 11.7 ns); (d) T = 60% Cr^{4+}:YAG (repetition rate of 65 kHz); (e) T = 80% Cr^{4+}:YAG (FWHM of 16.1 ns); (f) T = 80% Cr^{4+}:YAG (repetition rate of 420 kHz).

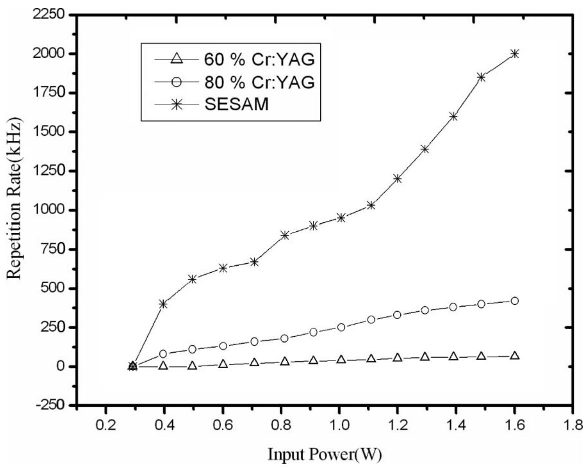

Fig. 3. Dependence of pulse repetition rate on incident pump power.

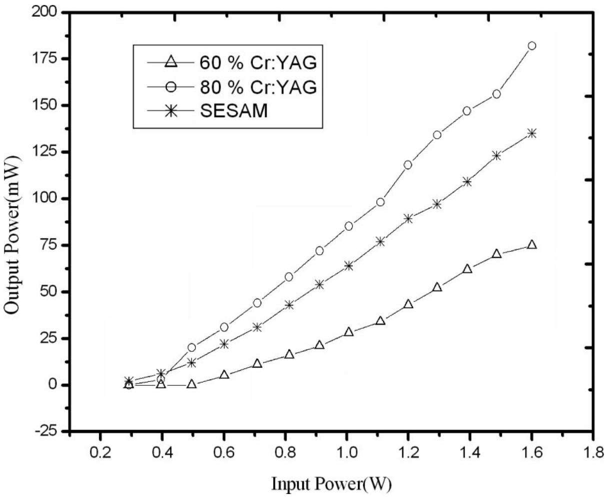

Fig. 4. Dependence of average output power on incident pump power.

was measured to be about 8.3 ns with a repetition rate as high as 2 MHz. The composite semiconductor absorber is composed of LT GaAs/$In_{0.25}Ga_{0.75}As$/GaAs and pure GaAs. Some parameters of the LT GaAs/$In_{0.25}Ga_{0.75}As$/GaAs layers can be adjusted freely so that we can achieve higher repetition rates or narrower pulse durations for Q switching.

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