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Experimental Investigation of Intracavity Absorber Low Temperature GaAs in Diode-Pumped Nd:$GdVO_4$ Laser

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A passively Q-switched and mode-locked diode-pumped Nd:$GdVO_4$ laser was demonstrated using a low-temperature-grown GaAs wafer (LT-GaAs) as an intracavity saturable absorber. The maximal Q-switched mode-locked average output power was 750 mW with the Q-switched envelop having a repetition rate of 167 kHz. The mode-locked pulse trains inside the Q-switched pulse envelope had a repetition rate of ~790 MHz. [DOI: 10.1143/JJAP.45.6268]

KEYWORDS: LT-GaAs, Nd:$GdVO_4$, Q-switched, mode-locked

1. Introduction

Q-switched and mode-locked (QML) lasers with high repetition rates and operating in the infrared spectral regions are required for various applications such as telecommunications, mid-IR remote-sensing, and ranging. A saturable absorber is a key unit device in passively Q-switched and mode-locked all-solid-state lasers and it determines mostly the pulse duration produced for a given laser host such as Nd:$GdVO_4$ used in this work. Thus far, a variety of solid-state saturable absorption materials for Q-switched and mode-locked lasers have been investigated, such as Cr^{4+}:YAG[1–5] crystals, LiF:F_2,[6] GaAs wafers,[7–9] and a semiconductor saturable absorption mirror (SESAM).[10–16] A GaAs wafer or a semi-insulating GaAs substrate is economical for passive Q-switched and mode-locked lasers, but its modulation depth is limited and cannot be controlled. For implanted GaAs, modulation depth can be controlled by the dose and speed of implantation. However, such type of GaAs is easily destroyed by a high-intensity laser. In this paper, we present another method of adjusting the modulation depth of GaAs. A GaAs absorber grown at a low temperature (LT-GaAs) was successfully fabricated. With such an optical intracavity saturable absorber, we demonstrated for the first time a Q-switched and mode-locked Nd:$GdVO_4$ laser pumped by a diode laser.

2. Low-Temperature Growth of GaAs Saturable Absorber

A GaAs absorber grown at a low temperature (LT-GaAs absorber) is shown in Fig. 1. The absorber was grown mainly using a metal organic vapor phase epitaxy (MOCVD) device. First, a 500 nm GaAs buffer layer was deposited on the semi-insulating GaAs substrate. Second, an GaAs layer approximately 3 µm was grown on the buffer layer at a temperature of as low as 550 °C. Third, the back of the GaAs substrate was polished and five pairs of SiO_2 and Al_2O_3 layers were antireflection coated on the LT-GaAs layer. Finally, the other side of the GaAs substrate was antireflection coated with five pairs of SiO_2 and Al_2O_3 layers at 1 µm. Due to these structural features, the LT-GaAs absorber could be directly used as an intracavity absorber. Compared with SESAMs, the LT-GaAs crystal is economically and easily fabricated. SESAMs are difficult to fabricate because

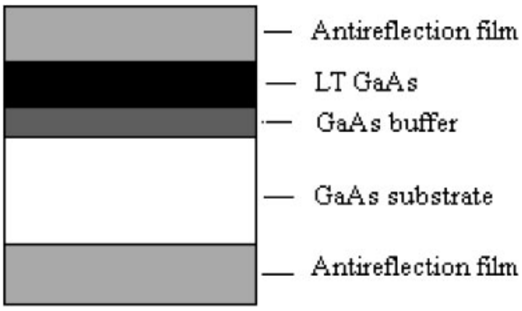

Fig. 1. Schematic of LT-GaAs absorber structure.

the facture procedure is very complicated. In the case of saturable Bragg reflector (SBR)-type SESAMs, the Bragg mirror is composed of multiple pairs of layers made of different types of semiconductor material. Furthermore, SESAMs used at 1 µm were composed of several GaAs/$In_{0.25}Ga_{0.75}As$ quantum well absorbers, which explains for the generation of strain in the interior of the SESAMs for the mismatch between GaAs and $In_{0.25}Ga_{0.75}As$. SESAMs' modulation depth increases with the thickness of the absorber layer. However, the strain also increases with the thickness of the absorber layer. The strain could shorten the life of SESAMs in use. In addition, such an absorber is easily fabricated and more economical than SESAMs. The LT-GaAs absorber has a longer life than that of the SESAMs because there is no mismatch between the LT-GaAs absorption layer and GaAs substrate. In the LT-GaAs absorber, modulation depth can be increased by decreasing the temperature of the GaAs absorption layer or increasing the thickness of the GaAs absorption layer, and recovery time decreases with growth temperature. Thus, the parameters for an LT-GaAs absorber are adjustable. To date, the principle for LT-GaAs as an absorber for Q-switching or mode locking is not very clear. As we know, single-photon absorption (SPA) involved in EL2 defects and two-photon absorption (TPA) between conduction and valence band plays an important role in Q-switching or mode locking.

3. Experimental Methods

Figure 2 shows the setup of the passively Q-switched and mode-locked Nd:$GdVO_4$ laser. The pump source was a fiber-coupled diode laser emitting at 808 nm with a maximum available output power of 8 W and a numerical

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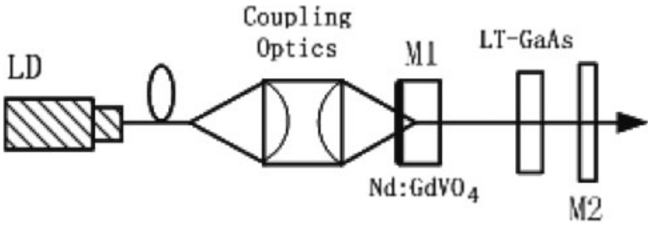

Fig. 2. Configuration of passively Q-switched and mode-locked Nd:$GdVO_4$ laser.

aperture of 0.12. The host crystal used here was *a*-cut Nd:$GdVO_4$ with a Nd^{3+} concentration of 1.3 at. % and dimensions of $3 \times 3 \times 4\,mm^3$. The output from the semiconductor laser was focused with a collimating lens onto the Nd:$GdVO_4$ crystal. The left side of the Nd:$GdVO_4$ crystal was coated to be highly reflective (HR, $R > 99.8\%$) at 1064 nm and antireflective (AR) at 808 nm pumping wavelength. It also acts as the input mirror M1. The other side of the crystal was coated to be AR at 1064 nm. The operating temperature of the laser crystal was kept at approximately 20 °C by water cooling. The output coupler M2 was a flat mirror with a 10% transmittance at 1.06 µm. The length of the flat–flat cavity was approximately 190 mm. The LT-GaAs absorber with an approximately initial transmittance of 95% at 1.06 µm was inserted into the laser cavity at the position close to the output coupler, where the laser beam spot size is at the minimum. We calculated the TEM_{00} Gaussian modes for the resonators used in the experiments by applying the ABCD-matrix formalism, and assuming that the pumped crystal can be modeled as a paraxial lens like medium. The mode radius upon the LT-GaAs absorber was approximately 130 µm at an incident pump power of 6.9 W.

The criterion for the transition between the regimes of cw mode locking and Q-switched mode locking has been investigated.[16] According to this criterion, the intracavity pulse energy must be smaller than the critical intracavity pulse energy that is required for obtaining a stable cw mode locking. We obtained QML, not cw mode locking. The modulation depth of the absorber related to the thickness of the absorber was an important parameter for the mode-locked laser. The mode radius upon the LT-GaAs absorber was also an important parameter. The radius of the diode laser was large, that is needed adjustment to obtain a high intensity. The pulse's temporal behavior was recorded using a Tektronix TDS 5104 digital phosphor oscilloscope (1 GHz bandwidth) and a fast photodiode detector (New Focus 1623) with a rise time of ~2 ns. Within the range of pump powers from 2.2 to 6.9 W, a modulation depth more than 90% of the output power of the mode-locked laser was achieved. The repetition rate was 100 kHz at the start, increased sharply up to 250 kHz and decreased to 167 kHz. The Q-switched pulse envelop had a temporal duration of 400–100 ns and the mode-locked pulses inside the Q-switched pulse envelope had a repetition rate of ~790 MHz, which corresponds to the roundtrip time of light traveling in the laser cavity. Figures 3(a) and 3(b) show the regular sequences of Q-switched pulses and a single Q-switched modulation pulse sampling from the train, respectively. The pulse-to-pulse amplitude fluctuation of the Q-switched pulse

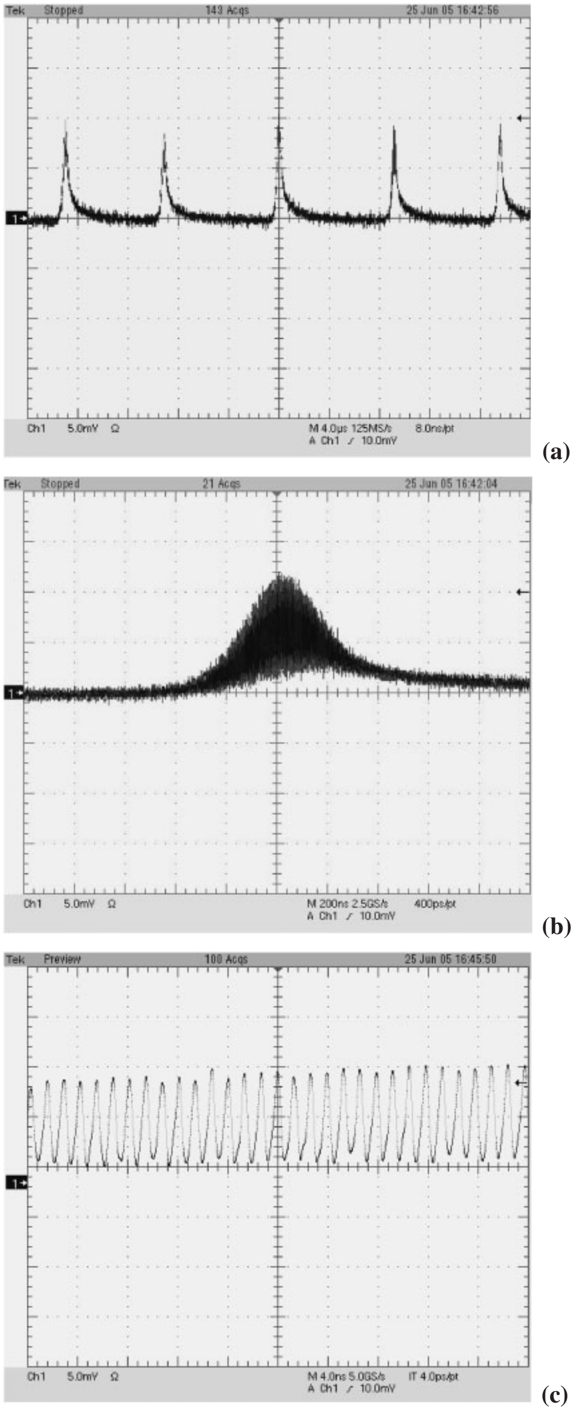

Fig. 3. (a) Q-switched and mode-locked laser pulse train. (b) Single Q-switched pulse sampling from train. (c) Pulse train of mode-locked pulses inside Q-switched envelope.

train was less than 15%. As shown in Fig. 3(c), simultaneous mode-locked pulse trains inside the Q-switched pulse induced by LT-GaAs were achieved. No damage to the LT-GaAs absorber was observed over hours of operation, and the laser performance was reproducible.

Figure 4 shows the cw and QML average output powers obtained using the 10% output coupler. The stable Q-switched and mode-locking modulations began to operate when the pump power exceeded 1.85 W. The optical slope efficiencies of the cw and the QML average output power curves were estimated to be 33 and 15%, respectively. At

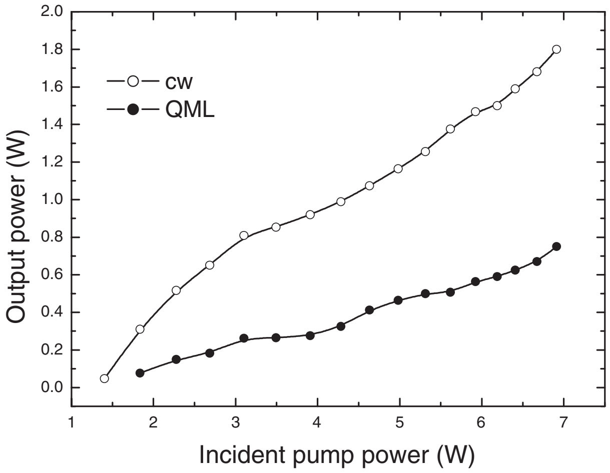

Fig. 4. Average output power versus incident pump power for cw and QML.

6.9 W incident pump power, the cw and the QML average output powers were 1.8 W and 750 mW, respectively. The corresponding repetition rate and the pulse envelope duration were about 167 kHz and 100 ns, respectively. The maximum energy and peak power of single the Q-switched pulse were 4.5 μJ and 45 W, respectively.

4. Conclusions

In conclusion, we have demonstrated for first time a passively Q-switched and mode-locked Nd:$GdVO_4$ 1064 nm laser with an intracavity LT-GaAs-saturable absorber using a simple flat–flat cavity. The mode-locked pulses inside the Q-switched pulse envelope had a repetition rate of ~790 MHz. The pulse-to-pulse amplitude fluctuation of the Q-switched pulse train was less than 15%. At the incident pump power of 6.9 W, the average output power of 750 mW was achieved and the corresponding peak power and energy of a single Q-switched pulse were 45 W and 4.5 μJ, respectively. In addition, with further optimization of modulation depth in the LT-GaAs wafer, this economical and compact device have various applications in operations requiring high peak power and high repetition rate.

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