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Passively Q-switched and mode-locked diode-pumped $Nd:YVO_4$ laser with LT-GaAs output coupler

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Abstract

We have demonstrated an efficient and compact passively Q-switched and mode-locked (QML) 1064 nm $Nd:YVO_4$ laser by using a low temperature grown GaAs (LT-GaAs) saturable absorber as well as an output coupler. Stable QML with envelope duration as short as 10 ns and Q-switched repetition rate of 36 kHz was obtained. It is the shortest envelope duration as far as we know, and it is so short that it can be used as Q-switching pulses directly. At 6.9 W of the incident pump power, average output power of 1.24 W was achieved and the corresponding peak power and energy of a single Q-switched pulse were 3.44 kW and 34.4 μJ, respectively. The mode-locked pulses inside the Q-switched pulse envelope had a repetition rate of 780 MHz.

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Keywords: LT-GaAs; $Nd:YVO_4$; QML

1. Introduction

Operating in the infrared spectral regions passively Q-switched and mode-locked (QML) lasers with high peak power have been studied for many years by using absorber such as $LiF:F_2$ [1], $Cr^{4+}:YAG$ [2–6], GaAs wafer [7,11] and semiconductor saturable absorption mirror (SESAM) [8–10]. In the early years, continuous wave (CW) modelocking was hard to realized. People had to pick up pico-second pulses from QML lasers by complicate techniques. But from 1992 then on, people have been able to obtain pico-second pulses from passive mode-locked lasers with SESAMs easily, which makes the study for QML laser less important than before. Besides that, QML pulses may have some other values such as higher peak powers than either mode-locked pulses or Q-switched pulses, which means that they may be used in the laser processing, laser marking and so on. However, the envelope duration of QML pulse is generally 100 ns or so by now, which makes it useless as Q-switching lasers.

In this paper, we first present QML by using a low temperature GaAs (LT-GaAs) saturable absorber. Stable QML with a 36 kHz Q-switched repetition rate and its envelope duration of 10 ns was obtained. It is the shortest envelope duration as far as we know, and it is so short that it can be used as Q-switching pulses directly. We can also obtain pure Q-switching by single frequency technique similar to [12].

2. LT-GaAs saturable absorber

GaAs wafer can be purchased from the market and the only working procedure is the coating. It is cheap and easy to fabricate. However, GaAs wafer is far away from the real application because of some of its weak points. First, the modulation depth of GaAs wafer is limited. The GaAs single crystal wafer is generally fabricated by

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liquid encapsulated czochralski (LEC) or vertical gradient freezing (VGF) methods so that there is only small amount of EL2 traps generated. As a result, the Q-switch or mode locking with GaAs absorber is always unstable. Second, some parameters of the GaAs wafer such as recovery time and modulation depth cannot be modulated freely.

GaAs absorber grown at low temperature (LT-GaAs absorber) is presented (as shown in insert of Fig. 1). The absorber was grown mainly by Metal Organic Vapor Phase Epitaxy (MOCVD) device. First, a 500 nm GaAs buffer layer was deposited on the semi-insulating GaAs substrate. Second, about 3 μm GaAs was grown on the buffer layer at the temperature as low as 550 °C. In order to make LT-GaAs to be an absorber as well as an output coupler directly, and to avoid the additional etalon effects caused by the residual back reflection, a quarter-wave of the hybrid of ZrO_2 and Y_2O_3(4:1) layer was antireflection coated on the LT-GaAs layer. Finally, the other side of the GaAs substrate was polished and coated a partial transmission layer at 1 μm containing seven pairs of Al_2O_3/SiO_2. Due to these features in structure, The LT-GaAs absorber can be used as the output coupler directly.

Compared with SESAMs, the LT-GaAs crystal is cheaply and easily fabricated. The SESAMs are difficult to fabricate because the procedure of facture is very complicate. For the case of saturable Bragg reflector (SBR) type of SESAMs, Bragg mirror composes of multiple pairs of layers made of different semiconductor material. Furthermore, the SESAMs used at 1 μm compose of several $GaAs/In_{0.25}Ga_{0.75}As$ quantum well absorbers, which answers for the generation of strain in the interior of the SESAMs for the mismatch between GaAs and $In_{0.25}Ga_{0.75}$ As. The SESAMs' modulation depth increases with the thickness of the absorber layer. However, the strain will increase with the thickness of the absorber layer too. The strain can shorten the life of the SESAMs in use. In addition, the LT-GaAs absorber has longer life than that of the SESAMs because there is no mismatch between LT-GaAs absorption layer and GaAs substrate. Fig. 1 shows the measured transmission spectrum of the LT-GaAs absorber, with a transmissivity of about 5% at 1064 nm. In LT-GaAs absorber, the modulation depth can be increased by decreasing the temperature of the GaAs absorption layer or increasing the thickness of the GaAs absorption layer, and the recovery time decreases with the temperature for growth. That is to say, the parameters for LT-GaAs absorber are adjustable. To date, the principle for the LT-GaAs as an absorber for Q-switch or mode locking is not very clear. As we know, single photon absorption (SPA) involved with EL2 defects and two-photon absorption (TPA) between conduction and valence band play an important role in Q-switching or mode locking.

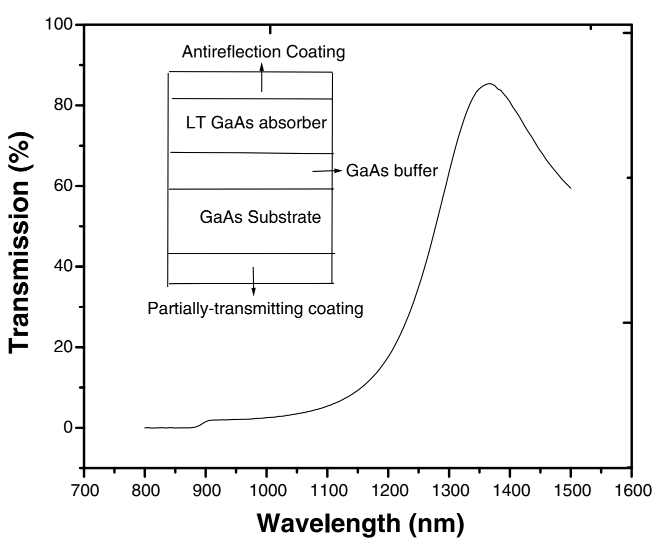

Fig. 1. Measured transmission spectrum of LT-GaAs absorber and the insert is its schematic structure.

3. Experimental

A schematic diagram for passively Q-switched and mode-locked $Nd:YVO_4$ laser is shown in Fig. 2. The pump source was a fiber-coupled diode laser emitting at 808 nm with the maximum available output power of 8 W and a numerical aperture of 0.12. The length of the concave–

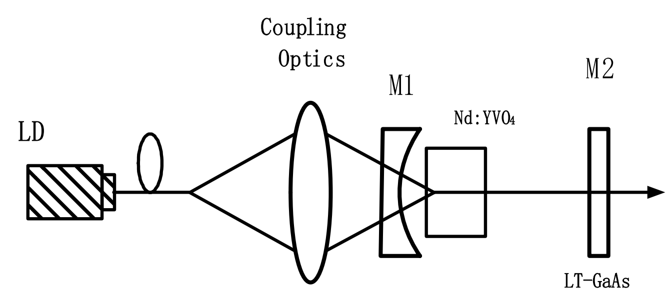

Fig. 2. Configuration of a passively Q-switched and mode-locked $Nd:YVO_4$ laser.

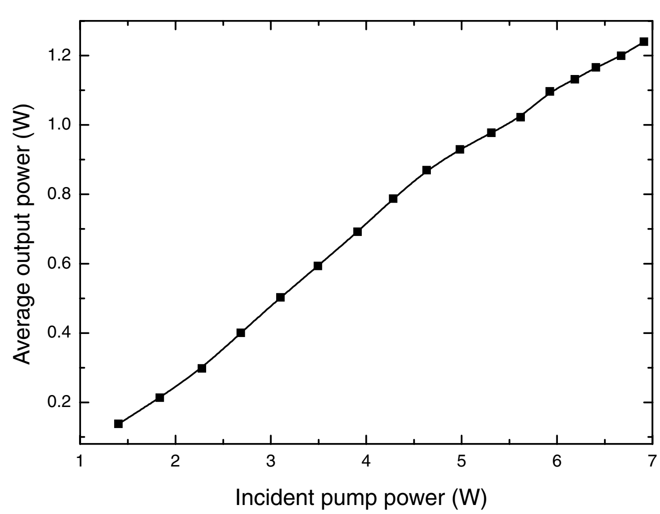

Fig. 3. Average output power versus incident pump power.

plane cavity was approximately 183 mm. The host crystal used here was a-cut $Nd:YVO_4$ with a Nd^{3+} concentration of 0.5 at% and dimensions of $4 \times 4 \times 8\ mm^3$. Both of its end faces were coated for antireflection at the lasing wavelength of 1064 nm and the pump wavelength of 808 nm. The operation temperature of the laser crystal was kept at about 20 °C by water cooling. The output from the semiconductor laser was focused with a collimating lens onto the $Nd:YVO_4$ crystal. The focused pump beam in the laser medium had an average diameter of about 700 μm. They were AR coated at 808 nm and 1.06 μm. The pump mirror M1 was a concave mirror with radius of 200 mm, highly reflectivity ($R > 99.8\%$) coated at 1.06 μm and high-transmission ($T > 95\%$) coated at 808 nm. The effectual cavity length accounted was about 192 mm. The LT-GaAs absorber is as both self-starting mechanics and output coupler M2, with the transmittance of 5% at 1.06 μm, which makes the insertion loss lower and the laser much more compact.

When the intracavity intensity of the laser is a little above the laser threshold, LT-GaAs crystal is an effective

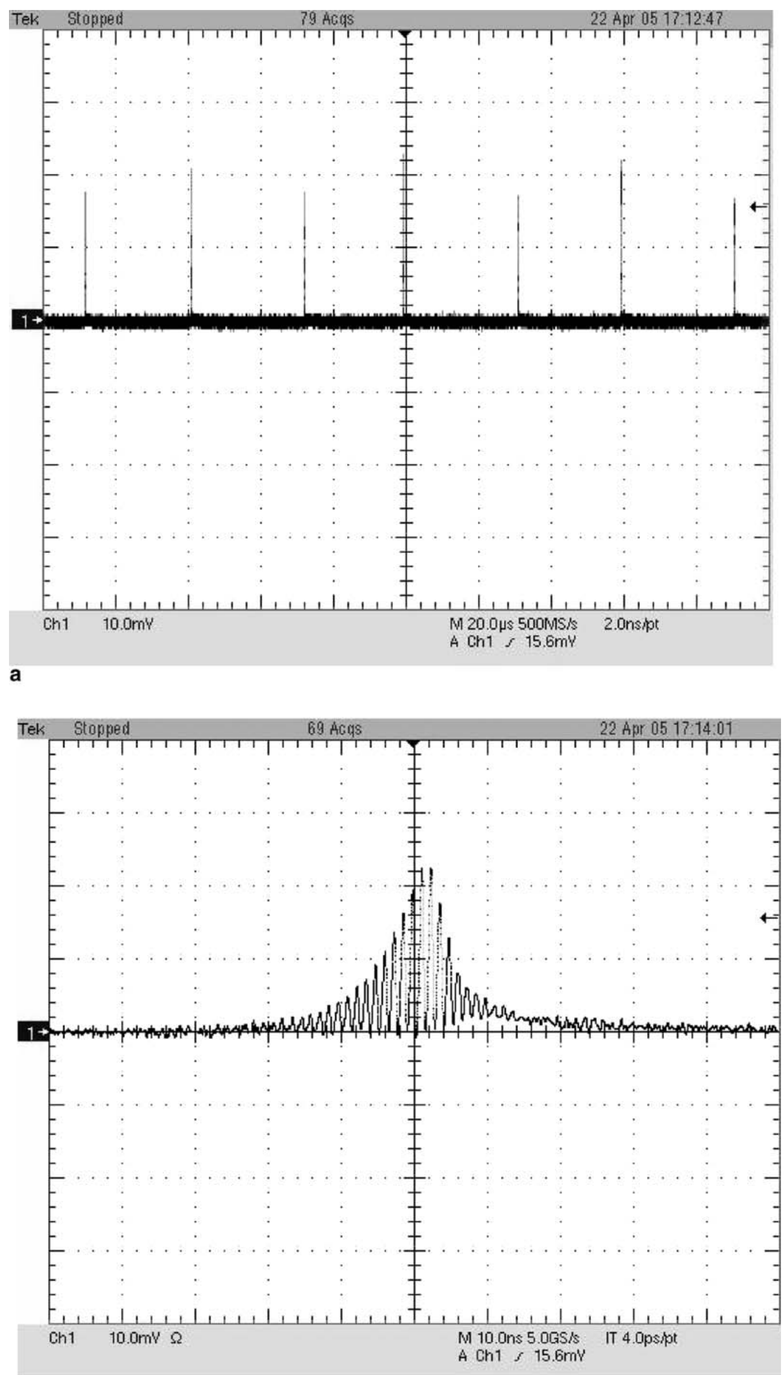

Fig. 4. Oscilloscope trace of a Q-switched and mode-locked laser pulse.

saturable absorber only for Q switching. To generate a QML pulse, the intensity fluctuation must be sufficiently strong. Therefore the beam area upon the LT-GaAs absorber is required to be small enough. We believe that the observed dependence of the mode-locking property on the cavity length may be caused by the laser beam size change on the saturable absorber. Considering the existence of the thermal lens effect in the gain medium, the laser beam size upon the saturable absorber is small with a long laser cavity, which enhances the mode-locking effect. We calculated the TEM_{00} Gaussian modes for the resonators used in the experiments by applying the ABCD-matrix formalism, and assumed that the pumped crystal can be modeled as a paraxial lens-like medium. The mode radius upon the LT-GaAs (output mirror) was calculated as where the laser beam spot size is at the minimum. When the cavity length is 183 mm, the mode radius upon the LT-GaAs absorber is about 125 μm at the incident pump power of 6.9 W.

We obtained QML, not cw mode locking. The criterion for the transition between the regimes of cw mode locking and Q-switched mode locking has been investigated. According to this criterion, the intracavity pulse energy must be smaller than the critical intracavity pulse energy which is required for obtaining stable cw mode locking [8,9]. The output behavior of the laser was observed with the changing of the pump power, as depicted in Fig. 3. The lasing oscillation of typical Q-switched threshold was about 1.4 W and the optical slope efficiency was estimated to be 20.5%. The stable partial mode-locking modulations began to operate when the pump power exceed 2.6 W. Within the range of pump power from 4.9 to 6.9 W, a perfect approximately 100% depth of modulation could be obtained. A maximum average output power of 1.24 W was obtained at an incident pump power of 6.9 W.

The pulse's temporal behavior was recorded by a Tektronix TDS 5104 Digital Phosphor Oscilloscope (1 GHz bandwidth) and a fast photodiode detector (NEW FOUCS 1623) with a rise time of ~2 ns. With an appropriate alignment of the laser cavity, stable 1064 nm pulse laser emission was achieved. The repetition rate increased from 10 to 36 kHz when the incident pump power increased from 1.4 to 6.9 W. The pulse duration decrease with the pump power increasing. The pulse width was about 400 ns at the start, then decreased sharply down to tens ns, and finally decreased to 10 ns. The mode-locked pulses inside the Q-switched pulse envelope had a repetition rate of ~780 MHz, which corresponds to the round trip time of light traveling in the laser cavity. The maximum energy and peak power of single Q-switched pulse was 34.4 μJ and 3.44 kW, respectively. A typical oscilloscope trace is presented in Fig. 4. No damage to the LT-GaAs absorber was observed over hours of operation, and the laser performance was reproducible.

4. Conclusion

In conclusion, we have first demonstrated a stable passively Q-switched and mode-locked $Nd:YVO_4$ solid-state laser with an output coupling LT-GaAs saturable absorber, using a simple concave–plane cavity. Stable QML with a 36 kHz Q-switched repetition rate and its envelope duration of 10 ns was obtained. To our knowledge, it is the shortest envelope duration and it is so short that it can be used as Q-switching pulses directly. At 6.9 W of the incident pump power, average output power of 1.24 W was achieved and the corresponding peak power and energy of a single Q-switched pulse was 3.44 kW and 34.4 μJ, respectively. The mode-locked pulses inside the Q-switched pulse envelope had a repetition rate of 780 MHz.

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