5.1-ps passively mode-locked $Nd:Gd_{0.42}Y_{0.58}VO_4$ laser with a LT-GaAs absorber

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We propose a diode end-pumped passively mode-locked $Nd:Gd_{0.42}Y_{0.58}VO_4$ ($Nd:GdYVO_4$) laser at 1064 nm using a GaAs absorber grown at low temperature as the output coupler. Stable continuous-wave (CW) mode locking with a 5.1-ps pulse duration at a repetition rate of 113 MHz is obtained. The maximum average output power is 2.29 W at the incident pump power of 12 W with the slope efficiency of about 24.8%.

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Over the past years, diode end-pumped passively mode-locked all-solid state lasers with semiconductor saturable-absorber mirrors (SESAMs) have attracted significant interest for their short-pulse duration, inherent simplicity, low cost, and reliable operation[1−3]. The neodymium-doped vanadate crystal($Nd:YVO_4$ and $Nd:GdVO_4$) has an especially high absorption coefficient for diode pumping and a large stimulated emission cross section, which are suited for achieving continuous-wave (CW) passive mode locking. Indeed, diode-pumped $Nd:YVO_4$ and $Nd:GdVO_4$ lasers, CW mode-locked with various solid-state saturable absorbers, have been demonstrated[4−7]. For further shortening the mode-locked pulses, it is necessary to broaden the gain bandwidth of the material. One of the possible ways is to use the disordered crystal host. Disordered crystals with inhomogeneous line broadening occupy intermediate position between ordered laser hosts and glasses with respect to their thermomechanical and spectroscopic properties. Recently, a new class of mixed vanadate crystal $Nd:Gd_{0.42}Y_{0.58}VO_4$ ($Nd:GdYVO_4$) has been developed[6−8]. The crystal is an isomorphism of $Nd:YVO_4$ and $Nd:GdVO_4$. From the view of structure, it can be considered that Y(Gd) is partially replaced by Gd(Y) in $Nd:Gd_{0.42}Y_{0.58}VO_4$. Currently, the new saturable absorber for achieving all-solid-state passive laser mode locking is still the specially designed semiconductor quantum-well structure, using a GaAs wafer which has advantages of easy fabrication, inexpensiveness, and high damage threshold. The diode-pumped $Nd:YVO_4$ and $Nd:GdVO_4$ CW mode-locked laser with a high-purity GaAs as the saturable absorber and the output coupler has been achieved successfully[9−11]. In this letter, we use a GaAs crystal grown at low temperature of 550 °C as the output coupler. The characteristics of Q-switched mode-locked (QML) and CW mode-locked $Nd:Gd_{0.42}Y_{0.58}VO_4$ laser at 1064 nm are studied. The CW mode-locked pulses have a pulse width of about 5.1 ps at a repetition rate of 113 MHz. When the pumped power is 12 W, the maximum output power of 2.29 W is obtained for the CW mode-locked laser, with a slope efficiency of about 24.8%.

To achieve CW mode-locking, a GaAs wafer is grown by the metalorganic chemical-vapor deposition technique (MOCVD). A 3-μm GaAs absorber layer is deposited on a 0.5-mm GaAs substrate at the low temperature of 550 °C. The other side of the GaAs substrate is coated with partial transmission film at a lasing wavelength of 1064 nm. And the top layer of the wafer is anti-reflectively coated at 1064 nm. The transmission of low temperature (LT)-GaAs wafer at 1064 nm is about 5%. The structure is shown in detail in Fig. 1. The schematic of the $Nd:Gd_{0.42}Y_{0.58}$ mode-locked laser at 1064 nm is shown in Fig. 2.

The pump source is a fiber-coupled diode laser emitting at 808 nm, whose maximum output power is 30 W. The radii of the pump beams are compressed to 0.32 mm on a host crystal. The host crystal is a-cut $Nd:Gd_{0.42}Y_{0.58}VO_4$ (with a Nd^{3+} concentration of 0.5 at.-% and dimensions of $3 \times 3 \times 10$ (mm)). Both of its

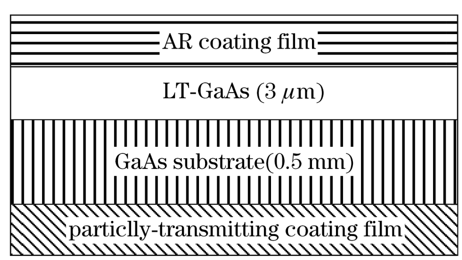

Fig. 1. Schematic structure of LT-GaAs wafer.

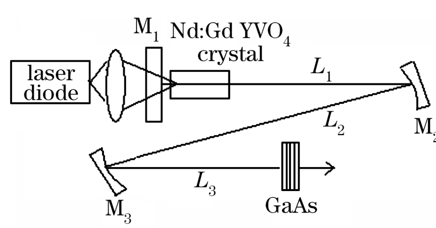

Fig. 2. Schematic of the $Nd:Gd_{0.42}Y_{0.58}VO_4$ laser.

light-passing faces are coated for anti-reflection (AR) at a lasing wavelength of 1064 nm and a pump wavelength of 808 nm. The resonator used in this experiment is a folded cavity composed of three reflection mirrors (M_1, M_2, M_3) and LT-GaAs. LT-GaAs is used as an output coupler and saturable absorber simultaneously. The outside face of M_1 is coated for AR at 808 nm and the inside face of M_1 is coated for high transmission (HT) at 808 nm and high reflection (HR) at 1064 nm. M_2 and M_3 are coated for HR at 1064 nm. M_1 is a flat mirror, M_2 and M_3 have radii of curvature of 500 and 100 mm, respectively. The arm lengths of three branches, L_1, L_2, and L_3, are approximately 480, 790, and 56 mm, respectively. Thus the total cavity length should be 1.326 m. The laser mode radii are estimated to be 30 μm on the GaAs and 310 μm inside the Nd:$Gd_{0.42}Y_{0.58}VO_4$ crystal.

Firstly, we demonstrate the diode pumped Nd:$Gd_{0.42}Y_{0.58}VO_4$ laser at 1064 nm in CW operation. We use an output coupler with the transmission of 4%. The output power is tested with a LP-3C power meter. When the pumped power is 12 W, the 1064-nm maximum output power is 5.22 W and the optical to optical efficiency is 43.5%, as shown in Fig. 3(a). Secondly, substituting the output coupler with GaAs wafer, we observe the generation of passively Q-switched mode-locked Nd:$GdYVO_4$ laser with a LT-GaAs wafer as saturable absorber and output coupler. In our experiment, the transmission of GaAs wafer at 1064 nm is about 5% and the function of average output power at mode-locked operation on pumping power is obtained. In the experiment, when the pumping power is between 2 and 5.6 W, Q-switched mode-locking is demonstrated. When the incident pumping power is 5.6 W, Q-switched mode-locked pulse with modulation depth of 100% is available. The Q-switched envelope train with repetition rate of 62.5 kHz and pulse duration of 600 ns is obtained. When the pumping power increases to 6 W, CW mode locking is obtained. The mode-locked output power increases to 2.29 W at the highest incident pump power of 12 W, giving a slope efficiency of 24.8%, as shown in Fig. 3(b).

Under the same experimental condition, the oscilloscope trace of a CW mode-locked pulse train is shown in Fig. 4. The output is detected by a high-speed photoreceiver and digital oscilloscope (Tek. TDS 5104). The mode-locked pulse repetition rate is about 113 MHz, which corresponds to the mode spacing of the laser-cavity length. Commercial autocorrelator (FR-103XL, Femtochrome Research, Inc.) is further used to characterize

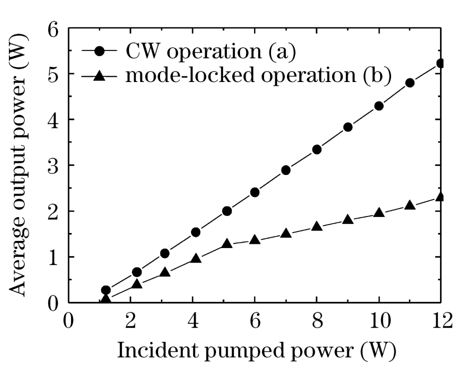

Fig. 3. Output power versus incident power.

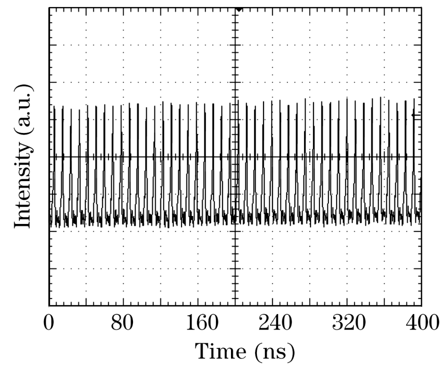

Fig. 4. Pulse train of the CW mode-locked Nd:$Gd_{0.42}Y_{0.58}VO_4$ laser.

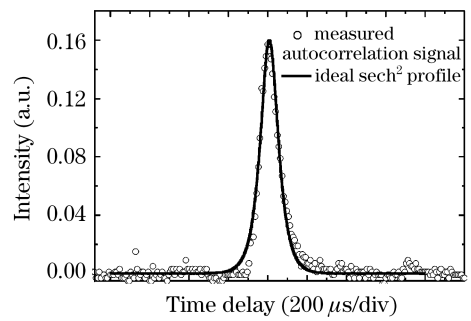

Fig. 5. Autocorrelation signal of CW mode-locked Nd:$Gd_{0.42}Y_{0.58}VO_4$ laser pulse.

the mode-locked pulses. A typical measured autocorrelation trace is shown in Fig. 5. Stable CW mode locking with a 5.1-ps pulse duration at a repetition rate of 113 MHz is detected. Figure 5 shows the profile of an autocorrelation signal with a full-width of half-maximum (FWHM) of 375 μs. Taking a hyperbolic secant ($sech^2$) profile (the smooth-fitting curve in Fig. 5), we estimate the pulse width to be 5.1 ps.

The narrower pulse width could be induced from two factors. One is that the nonlinearity in the GaAs is enhanced in the current folded-mirror cavity design through the smaller focused beam compared with that in the two-mirror cavity; the other may be attributed accordingly to the broader gain bandwidth of mixed vanadate crystal. It is noted that the obtained pulse width is a few times narrower than that achieved in the mode-locked Nd:$GdVO_4$ laser with the same GaAs absorber mirror[12].

In conclusion, using a four-mirror laser cavity and GaAs crystal grown at low temperature as the output couple, passively CW mode-locked Nd:$Gd_{0.42}Y_{0.58}VO_4$ laser at 1064 nm with a 5.1-ps pulse width at a repetition rate of 113 MHz is successfully demonstrated. The maximum average output power of 2.29 W is obtained with a slope efficiency of 24.8%. Our experimental results show that Nd:$Gd_{0.42}Y_{0.58}VO_4$ could potentially be used for high-power, ultra-short-pulse lasers. In particular, its broader emission spectrum bandwidth makes it favorable over other Nd-doped gain media for the purpose.

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