

Simultaneous mode locking in a diode-pumped passively Q-switched Nd:YVO₄ laser with a GaAs saturable absorber

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Simultaneous mode locking and Q switching is accomplished in a diode-pumped Nd:YVO₄/GaAs laser. The average output power is ~2.0 W at 10.6-W absorbed pump power, and the repetition rate of the Q-switched pulse is ~120 kHz. The mode-locked pulse inside the Q-switched pulse has a repetition rate of ~148 MHz, and its average duration is estimated to be ~100 ps. © 2001 Optical Society of America
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1. Introduction

Simultaneous Q switching and mode locking is of great interest for the generation of high peak power and ultrashort pulses. The nonlinear absorption of saturable absorbers was first successfully employed for simultaneous Q switching and mode locking of solid-state lasers in 1965.^{1,2} Unlike cw mode locking,³ to generate a Q-switched and mode-locked pulse, the intensity fluctuation must be sufficiently strong and the build-up time of the Q-switched pulses must be sufficiently short because of the limited round-trip time of the intensity fluctuation. In early technologies, dyes were commonly employed in pulsed mode-locked solid-state lasers. Recently, the generation of passively Q-switched and mode-locked pulses was performed in diode-pumped solid-state lasers with Cr⁴⁺:YAG.^{4,5} Semiconductor GaAs was first used for passive mode locking by Zhang *et al.*⁶ and by Kubecek *et al.*⁷ in a flash-lamp-pumped solid-state laser and for passive Q switching by Kajava and Gaeta⁸ for a diode-pumped Nd:YAG laser. Kajava and Gaeta⁸ concluded that two-photon absorption

and free-carrier effects play an important role in the pulse formation in GaAs. Recently, Jiang *et al.*⁹ used an antireflection-coated semiconductor saturable-absorber mirror to generate cw mode locking. In addition to semiconductor materials, other solid-state saturable absorbers such as colored glass filters¹⁰ and semiconductor-doped glasses¹¹ were also used for mode-locked lasers. Here we report that GaAs can be used for simultaneous Q switching and mode locking in a diode-pumped Nd:YVO₄ laser.

The fluctuation mechanism is believed to be responsible mainly for the generation of ultrashort pulses in lasers Q switched by nonlinear absorbers.^{12,13} According to this mechanism, the picture of ultrashort pulse formation is the following. During the linear stage of generation, the intensity fluctuations arise because of the interference of a great number of modes having a random phase distribution so that the radiation consists of a chaotic collection of ultrashort peaks. In the nonlinear stage, where bleaching of the absorber takes place, the most intensive fluctuation peaks are compressed and amplified faster than all the weaker ones. Kryukov and Letokhov¹³ used the fluctuation mechanism to prove that the ratio of peak pulse power to the mean background power can be given by

$$\frac{P_m}{P_{\text{background}}} \cong (\ln m)^\mu, \quad (1)$$

where m is the number of axial modes at the end of the build up of the linear stage and μ is the nonlinear parameter related to the pulse compression in the nonlinear stage of development. To obtain a high

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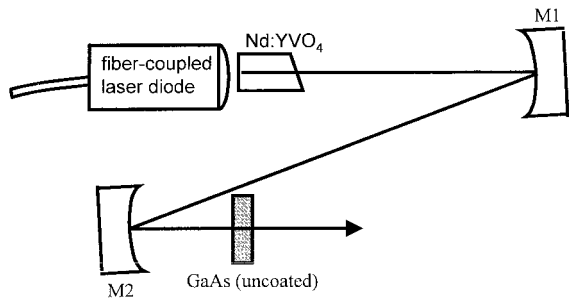


Fig. 1. Configuration of a passively Q -switched mode-locked Nd:YVO₄ laser with an uncoated GaAs.

pulse-to-background ratio, m and μ should be as large as possible.

During the linear stage of the intensity fluctuation build up, the number of axial modes decreases because of the natural gravitation toward the center of the amplification line as given by¹³

$$m = \frac{m_0}{[g_0(t_b/t_r)]^{1/2}}, \quad (2)$$

where m_0 is the initial number of axial modes, g_0 is the threshold gain, t_r is the round-trip time, and t_b is the pulse build-up time. In most cases the nonlinear parameter is given by¹³

$$\mu = \frac{1 - T_0}{t_b(dg/dt)}, \quad (3)$$

where T_0 is the initial transmission of the saturable absorber and dg/dt is the speed of the gain increase that is due to threshold pumping. From Eqs. (1)–(3) it can be found that a shorter pulse build-up time generally leads to a larger m and a larger μ , and then a higher pulse-to-background ratio.

We designed a 1-m-long cavity to have a large number of axial modes for a high pulse-to-background ratio in pulsed mode-locking performance. Figure 1 outlines the basic laser setup. The pump power is a 20-W fiber-coupled diode-laser array (Coherent FAP-81-20C-800-B) with an output wavelength at 25 °C in the 807–810-nm range. The fibers were drawn into round bundles of 0.8-mm diameter with a numerical aperture of 0.18. A focusing lens with 20-mm focal length and 85% coupling efficiency was used to reimage the pump beam onto the laser crystal. The waist diameter of the pump beam was approximately 400 μm . The a -cut 0.3-at. % Nd³⁺, 10-mm-long Nd:YVO₄ crystal was a 0.5° wedge and was coated for high reflectivity at 1064 nm ($R > 99.9\%$) and for high transmission at 808 nm ($T > 95\%$) on one side. The other side was antireflection coated at 1064 nm. We used a Nd:YVO₄ crystal with a low doping concentration to avoid thermally induced fractures.¹⁴ The laser crystal was wrapped in indium foil and was mounted in a water-cooled copper block. The water temperature was maintained at 20 °C. We designed the cavity to allow for easy mode matching with the pump beam and to provide the proper spot size in the

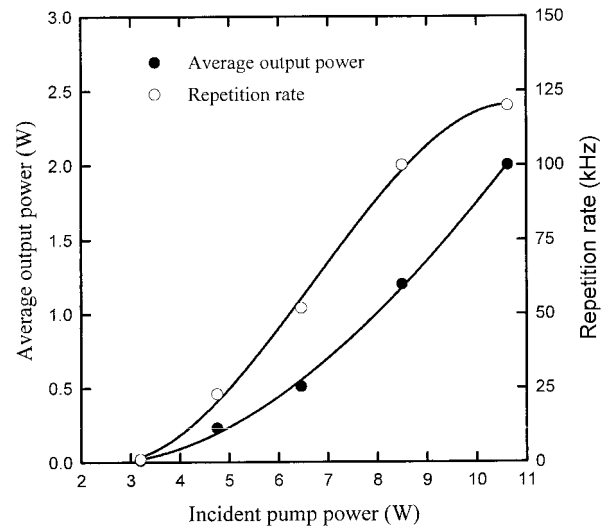


Fig. 2. Average output power and repetition rates of a passively Q -switched mode-locked pulse train with respect to pump power.

saturable absorber. An uncoated 0.3-mm-thick GaAs wafer was used as the saturable absorber. The GaAs wafer also served as an output coupler in the cavity because the uncoated GaAs forms a Fabry–Perot cavity. Use of a GaAs wafer as a saturable absorber and as an output coupler has been demonstrated in a passively diode-pumped Q -switched laser.¹⁵ The effective reflectivity of the GaAs output coupler is approximately 70%. The resonator consisted of two spherical highly reflective (at 1064 nm) mirrors, M1 and M2, with radii of curvature of 50 and 10 cm, separated by 60 cm. Since a short pulse build-up time is of benefit to the generation of Q -switched and mode-locked pulses, the GaAs saturable absorber was placed at a tight focusing position to allow for a short build-up time. For this purpose, the distance between the GaAs and mirror M2 was fixed at between 5.4 and 5.6 cm.

Figure 2 shows the average output power with respect to the incident pump power. The average output power was ~ 2.0 W at 10.6-W absorbed pump power and the repetition rate of the Q -switched pulse was ~ 120 kHz. The lasing threshold and optical slope efficiency were 3.2 W and 26.5%, respectively. The experimental results showed that the Q -switched pulse train became irregular when the pump power exceeded 11 W because the modulation depth of the present GaAs absorber was not high enough. Even so, the output power can be scaled up to 4.2 W at a 17-W absorbed pump power. This result indicates that the unsaturable loss of the GaAs wafer is not significant. The pulse temporal behavior was recorded with a LeCroy 9362 oscilloscope (500-MHz bandwidth) and a high-speed InGaAs photodiode with a rise time of ~ 0.1 ns. A typical oscilloscope trace is presented in Fig. 3, showing a train of Q -switched pulses. The pulse-to-pulse amplitude fluctuation of the Q -switched pulse train was found to be less than $\pm 10\%$. The Q -switched pulse envelope

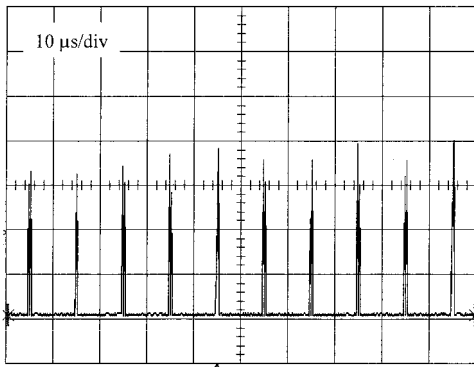


Fig. 3. Oscilloscope traces of a train of Q -switched pulses.

has a temporal duration of 200–300 ns and the mode-locked pulses inside the Q -switched pulse have a repetition rate of ~ 148 MHz, as shown in Figs. 4(a) and 4(b). The temporal duration of the mode-locked pulses was estimated to be ~ 100 ps. The peak power of a single pulse near the maximum of the Q -switched envelope was between 1 and 3 kW. This peak power is several times higher than a passive Nd:YVO₄/GaAs laser without mode locking.¹⁵ During the experiment, the temperature rise of the GaAs wafer was not significant, and we did not observe any optical damage to the GaAs wafer.

Based on the fact that the mode radius inside the GaAs is 30 μm and the energy of the average mode-locked pulse in the cavity is 180 nJ, the fluence inside the GaAs can be estimated to be 6.4 mJ/cm^2 . The intensity-dependent absorption coefficient is given by $\alpha = \alpha_0 / (1 + I/I_{\text{sat}})$, where α_0 is the absorption coef-

ficient and I_{sat} is the saturation fluence. Using $\alpha_0 = 1.1 \text{ cm}^{-1}$ and $I_{\text{sat}} = 1.6 \text{ mJ}/\text{cm}^2$,⁸ we found the double-pass small-signal transmission to be 98.7%, which means that the GaAs is strongly saturated. Note that an uncoated GaAs serves as a narrow-band Fabry–Perot filter that has a direct effect on pulse formation. The effective bandwidth of an uncoated GaAs is

$$\Delta\nu = \frac{c}{2nd} \left(\frac{1-R}{\pi\sqrt{R}} \right), \quad (4)$$

where c is the speed of light in vacuum; n and d are, respectively, the refractive index and the thickness of the GaAs; and R is the Fresnel reflection. With Eq. (4), the effective bandwidth is found to be ~ 60 GHz. The gain bandwidth of the Nd:YVO₄ crystal is ~ 250 GHz. Therefore, the narrow-band Fabry–Perot filter that results from the uncoated GaAs has a direct effect on pulse formation.

In conclusion, we have, for the first time to our knowledge, demonstrated the use of uncoated GaAs to obtain a high-power diode-pumped Q -switched and mode-locked Nd:YVO₄ laser. The laser provided Q -switched pulses of 200–300-ns duration, an ~ 100 -ps mode-locked pulse train, and 1–3-kW peak power. With further optimization of the modulation depth in the GaAs wafer, this laser can be of considerable interest for a variety of applications.

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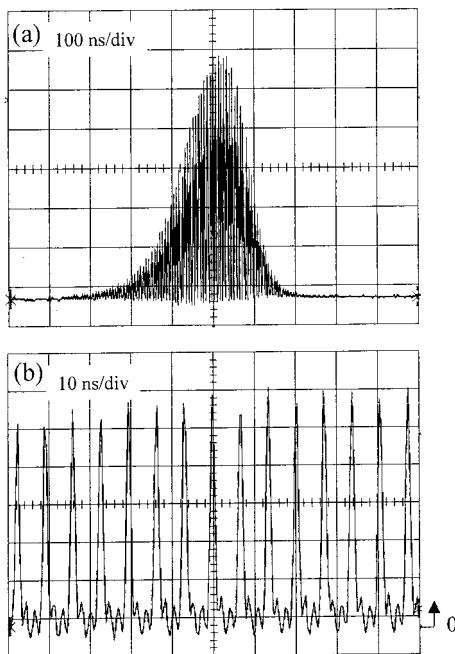


Fig. 4. (a) Expanded temporal shape of a single Q -switched pulse. (b) Oscilloscope traces of a train of mode-locked pulses.

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