

Q-switched mode-locked diode-pumped Nd:YVO₄ laser with a saturable Bragg reflector

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We demonstrated a diode-pumped passively *Q*-switched mode-locked Nd:YVO₄ laser by using a relaxed saturable Bragg reflector (SBR). Stable mode-locked pulse train with the repetition rate of ~230 MHz was achieved and the pulse train was modulated by the *Q*-switched envelope with the repetition rate of ~150 kHz. The maximum output of 4 W was obtained under the pump power of 13.5 W. The optical-to-optical efficiency was 30%. We also discussed the transition of each process having emerged.

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Passively *Q*-switched solid-state lasers achieved by saturable absorber have played an important role in the development of laser technique in the past years. Compared with the actively *Q*-switched lasers, the passively *Q*-switched lasers should be more favorable because the saturable absorbers are inexpensive, with fast recovery time and wide spectral range. Furthermore, one of the significant advantages is its compactness making the simple cavity configuration.

It is well known that passive *Q*-switching strongly depends on the availability of saturable absorbers. Successful *Q*-switching has been achieved by different saturable absorbers, such as LiF:F²⁻, Cr⁴⁺:YAG, GaAs, and antiresonant Fabry-Perot saturable absorber^[1-4]. With the development of semiconductor growth technology and band gap engineering, a novel saturable absorber called saturable Bragg reflector (SBR) has been developed, which can generate passive mode-locking in dependence on the practical situation. In general, SBR is composed of a highly reflective mirror stack (> 99%) and single or double quantum wells, thus SBR can act duplex roles, one is as a cavity mirror and another is as a saturable absorbing medium. The passively mode-locked solid-state lasers has been demonstrated by using SBR for various solid-state laser, especially those laser hosts with long upper state lifetimes, e.g. Nd:YVO₄^[5,6] and Nd:GdVO₄^[7,8]. In most of the previous papers, the attention was focused on the continuous-wave (CW) mode-locking operation. However, for some applications, such as nonlinear frequency conversion, microstructure fabrication, and medical applications, the pure passive *Q*-switching and *Q*-switched mode-locking (QML) are attractive because much more energy is concentrated in the *Q*-switched envelope. In this letter, we report the diode-pumped *Q*-switching and QML Nd:YVO₄ lasers by using a SBR.

The schematic of the laser configuration is shown in Fig. 1. The pump source is a fiber-coupled diode laser emitting at 808 nm. A focus lens is used to reimage the pump beam with the radius of 0.32 mm on the host crystal. An *a*-cut 3×3×10 mm³ Nd:YVO₄ crystal is coated for antireflection ($R < 0.2\%$) at lasing wavelength of 1064

nm and pump wavelength of 808 nm on both faces. To compress the thermal lensing effect and avoid thermally induced fracture, we choose the Nd:YVO₄ crystal with the low doping concentration of 0.27 at.-%^[9]. The resonator used in this experiment is a fold-cavity composed of three mirrors and a SBR. M_1 is a flat reflective mirror. M_2 , with a 50-cm radius-of-curvature concave, has the partially reflective coating with the transmissivity of $T = 15\%$ at the lasing wavelength of 1064 nm, is used as an output coupler, which should have the equivalent output coupling of ~30% because of dual-pass outputs. Another fold-mirror M_3 , a 10-cm radius-of-curvature concave mirror, has the highly reflective coating at the lasing wavelength. L_1 , L_2 , and L_3 , the arm lengths of three branches in the fold-cavity, are about 20, 40, and 6 cm, respectively. To optimize mode matching and suppress high-order transverse modes, the cavity is designed as the pump mode size which is smaller than the laser mode size inside the gain medium^[10]. The laser mode radii are estimated to be about 35 μm on the SBR and about 400 μm inside Nd:YVO₄ crystal. It is noted that Nd:YVO₄ crystal is used to achieve CW mode-locking successfully, however the process of QML is indispensable in its full course. In this paper, we do not emphasize the process of CW mode-locking, but the transition from QML to CW mode-locking instead.

SBR used in our experiment was grown by molecular beam epitaxy without any post-processing. It consists of 35 pairs of GaAs/AlAs quarter-wave Bragg layers having the high reflectivity (> 99.5%) at 1064 nm and

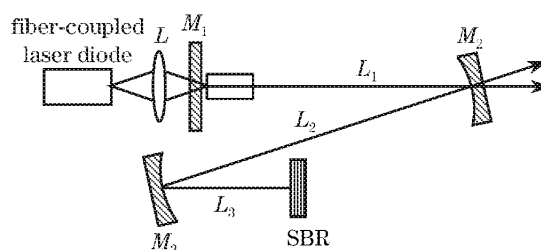


Fig. 1. Configuration of a passively *Q*-switched mode-locked Nd:YVO₄ laser with a SBR.

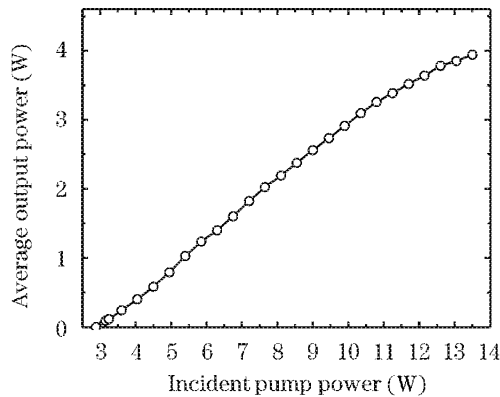


Fig. 2. Dependence of the average output power on the incident pump power.

a 7-nm relaxed $\text{In}_{0.3}\text{Ga}_{0.7}\text{As}$ single-quantum-well. The important physical parameters of the present SBR used here are modulation depth of 1.0%, non-saturable loss of 0.2%, saturation fluence of $40.0 \mu\text{J}/\text{cm}^2$, and recovery time of ~ 20 ps.

The behavior of the laser average output power as a function of the available incident pump power was investigated as shown in Fig. 2. The oscillation threshold is about 2.88 W. Within the range of pump power from 2.88 to 3.24 W, the laser is in the CW operation regime. When the pump power is slightly increased over 3.24 W, the Q-switching tendency of the laser immediately emerges. When the pump power is further increased until 3.6 W, the Q-switching operation becomes more clear, however, each Q-switched pulse is extremely unstable in amplitudes and the Q-switched pulse train does not have perfect periodicity, as shown in Fig. 3(a). When the pump power is around 3.6 W, the Q-switched pulse train becomes relatively stable in amplitude but the laser output consists of the Q-switched pulse train underneath a periodically modulated envelope, and the periodicity

of the Q-switched pulse train is imperfect as shown in Fig. 3(b). When the pump power is higher than 3.6 W, the laser initiates into the regime of the stable passively Q-switching, the pulse train has nearly the perfect periodicity with the repetition rate of about 133 kHz, and the stable Q-switching has been completely achieved, as shown in Fig. 3(c). When the pump power is slightly higher than 4.05 W, the laser operation state transits into the QML tendency, in this moment the Q-switched pulse is broadened, at the top of the Q-switched pulses very weak modulations occur, and the mode-locking begins to start, as shown in Fig. 4(a). As the pump power is increased, the QML tendency becomes clear, the Q-switched envelope is broadened further, and the shape like the beat appears, as shown in Fig. 4(b). It is obvious that the QML is incomplete with the modulation depth of 50%. Until the pump power increases to 5.85 W, the modulation depths of pulse train underneath the Q-switched envelope deepen and each Q-switched envelope expands further, finally connects with its two neighbors. The range of pump power from 4.05 to 5.85 W is an interim regime from the typical Q-switching to the complete QML. When the pump power is slightly over 5.85 W, the laser exhibits the typical QML operation. Until the pump power is increased to 13.5 W, the laser always operates at the QML regime. The pulse train has the repetition rate of 227.3 MHz which is determined only by the cavity length, and the pulse train is modulated with a strongly peaked Q-switched envelope that has a full width at half maximum (FWHM) of about $3.8 \mu\text{s}$, much larger than 400 ns of the ideal Q-switching shown in Fig. 3(c). The typical QML pulse train, which has the characteristic that the mode-locked pulses are underneath the Q-switched envelope, is shown in Fig. 4(c). Under the maximum incident pump power of 13.5 W, we obtain the maximum average output power as high as 4 W in the QML operation, corresponding to the optical-to-optical efficiency of about 30%.

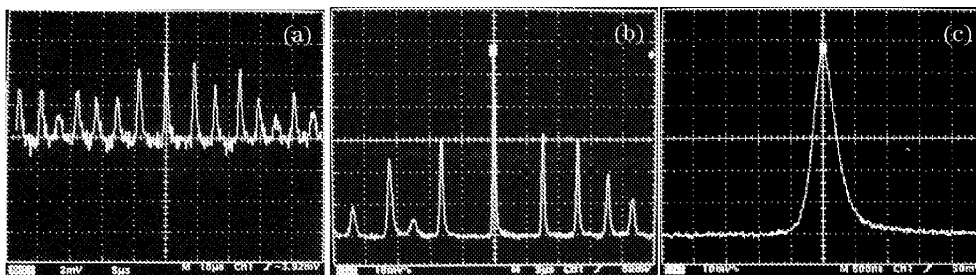


Fig. 3. (a) An instable Q-switched pulse train; (b) a stable Q-switched pulse train; (c) detail of an individual Q-switched pulse.

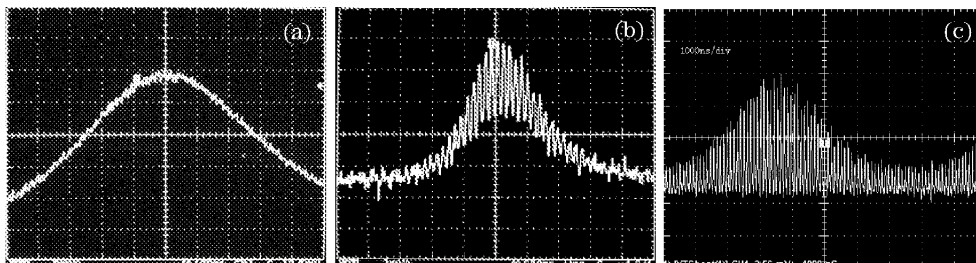


Fig. 4. Oscilloscope traces of a Q-switched mode-locked pulse. (a) The QML tendency ($P_{in} = 4.1$ W); (b) a Q-switched mode-locked pulse train with the modulation depth of 50% ($P_{in} = 5.0$ W); (c) the complete QML ($P_{in} = 6.0$ W).

We now give the analysis and discussion for the dynamic behavior of the diode pumped Nd:YVO₄ laser with a saturable Bragg reflector.

The criterion of stable CW mode-locked operation for against QML is introduced as^[10]

$$E_{p,c} = (E_{\text{sat,L}} E_{\text{sat,A}} \Delta R)^{1/2} \\ = (F_{\text{sat,L}} A_{\text{eff,L}} F_{\text{sat,A}} A_{\text{eff,A}} \Delta R)^{1/2}, \quad (1)$$

where ΔR , the modulation depth of the SBR, is 1.0% in our case. $E_{p,c}$, the critical intracavity pulse energy, is the minimum intracavity pulse energy required for obtaining stable CW mode locking, that is to say in theory stable CW mode locking can be obtained for $E_p > E_{p,c}$, otherwise QML is obtained. It should be noticed that $E_{p,c}$ is not a constant because of the dependence of laser mode radii on the SBR (ω_A) and in the crystal (ω_L) on the pump power. From Fig. 5 we can derive that the product of ω_L and ω_A decreases with the increasing of the pump power, then $E_{p,c}$ diminishes (i.e. the tendency of CW mode-locking is reinforced) as the pump power is enhanced. Then we only need to consider the top pump power of 13.5 W, which corresponds to the maximum output power of 4 W, the highest intracavity pulse energy, and the least critical intracavity pulse energy in the meantime. When the output power reaches 4 W, we get $\omega_L \approx 510 \mu\text{m}$, $\omega_A \approx 22.5 \mu\text{m}$, and $P = 11.3 \text{ W}$ through

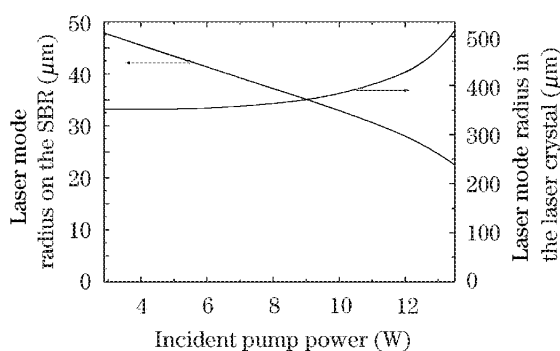


Fig. 5. Dependence of the laser radii on the SBR and in the laser material on the incident pump power.

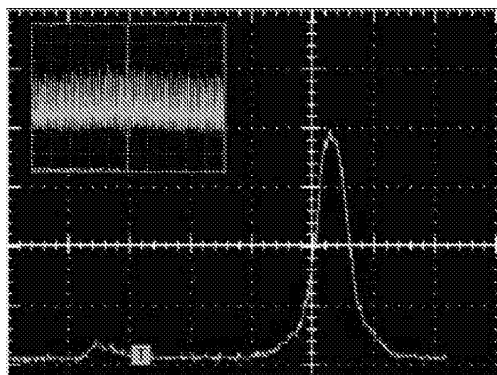


Fig. 6. Oscilloscope trace of 11.2-ps pulse (inset: CW mode-locked pulse train with a repetition rate of 230 MHz).

$P = \frac{1}{2} P_{\text{out}} \frac{1+R}{1-R}$, where P_{out} is the corresponding output power and R is the reflectivity of the output mirror. There is a definition $E_p = PT_R$ (T_R is the cavity round-trip time), and it is easy to figure out $E_p \approx 5 \times 10^{-8} \text{ J}$, and $E_{p,c} \approx 14 \times 10^{-8} \text{ J}$. It is obvious that even the largest intracavity pulse energy is lower than the critical intracavity pulse energy, so we still achieve QML.

Finally, for given values of ΔR and $E_{\text{sat,A}}$, in order to suppress QML and obtain the CW mode-locked operation, we increased the intracavity pulse energy E_p by changing the output coupling with small transmission. In our experiment, the output coupling was replaced with the transmission of $T_{\text{oc}} = 4.3\%$. When the pump power was about 11 W, the stable CW mode-locked state appeared with the output power of 3.6 W. Thus, according to above analysis, E_p was roughly equal to $17 \times 10^{-8} \text{ J}$, more than $E_{p,c}$, so we obtained the CW mode-locked state, which is according to the argument advanced in Ref. [10]. The pulse duration was measured to be 11.2 ps by using an intensity autocorrelator (FR-103XL, Femtochrome, Research Inc.). The typical autocorrelation trace of the pulses is shown in Fig. 6.

In conclusion, we reported a passively Q-switched mode-locked Nd:YVO₄ laser by using a SBR, and obtained $\sim 230 \text{ MHz}$ mode-locked pulse train underneath Q-switched pulse trains with the repetition rate of 150 kHz. QML average power of 4 W was achieved corresponding to pump power of 13.5 W, and the overall optical-to-optical efficiency reached 30%.

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