Multi-watt Q-switched Nd:YVO_4 laser with GaAs output coupler

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A passively Q-switched operation of a diode-pumped Nd:YVO_4 laser is demonstrated, in which a GaAs film is used as the saturable absorber as well as the output coupler. At the pump power of 10 W, a stable fundamental-mode average power output of 2.11 W was obtained with a pulse duration of 140 ns, pulse energy of 76 μJ and pulse repetition rate of 28 kHz. A theoretical analysis that describes the passive Q-switching dynamics of GaAs is presented.

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Passive Q-switching of the solid-state lasers with solid-state saturable absorber is economical, simple and practical[1−4]. In recent years, semiconductor saturable absorbers as passive Q-switches have attracted a great deal of attention. Passive Q-switching of solid-state lasers have been demonstrated by using bulk InGaAsP film[5], the antiresonant Fabry-Perot saturable absorber[3] and GaAs[4,6]. In comparison with previous saturable absorbers such as dyes and LiF:F_2^- color center crystals, semiconductor saturable absorbers are more photochemically and thermally stable and have a higher damage threshold. On the other hand, with the existing technology in epitaxial growth, band gaps of compound semiconductors can be engineered to cover almost the entire spectral range from visible to infrared, so that all solid-state lasers may essentially be Q-switched by suitable compound semiconductors[5].

Recently, semiconductor GaAs was reported to be used as passive Q-switch in diode-pumped Nd:YAG laser[4,7], Nd:$Sr_5(PO_4)_3F$ laser[6] and Nd:YVO_4 laser[8]. In these lasers, the average powers have been generally limited to a few hundred milli-watts. However, in many applications, such as material processing, achieving higher average power than this is of great importance, even if it involves some small compromise on pulse width over the minimum achievable. Reports on multi-watt all-solid state passively Q-switched lasers are still rather scare. In this letter, we report on a passive Q-switching Nd:YVO_4 laser using a semiconductor GaAs wafer as passive Q-switch as well as an output coupler. At the pump power of 10 W, a stable fundamental-mode average power output of 2.11 W was obtained with a pulse duration of 140 ns, pulse energe of 76 μJ and pulse repetition rate of 28 kHz, and with no evidence of damage on the saturabe absorber. Furthermore, we present the Q-switching dynamics of GaAs and give an attempt to explain some phenomenon observed in the experiment. Both theory analyses and experimental results all show that GaAs is a practical and efficient Q-switch.

Because the photon energy at 1.06 μm wavelength is far below the GaAs band gap of 1.42 eV, the absorption at this wavelength is believed due to the EL2 defect that forms a deep donor level $EL2^0/EL2^+$ located 0.82 eV below the conduction band within the band gap[4]. EL2 is a defect energy level that exists in undoped GaAs to compensate the shallow acceptors caused by the chemical stain of carbon during the growth of GaAs[9]. Under laser illumination, transitions from $EL2^0$ to the conduction band absorb optical energy and produce free electrons in conduction band and positively charged donors $EL2^+$, while valence to $EL2^+$ transitions produces free holes in valence band and neutral donors $EL2^0$. The absorption coefficient for this process is saturable with the increase in laser irradiance in GaAs and we name this absorption as single-photon absorption (SPA). There is a general understanding that GaAs can be used as passive Q switch as a result of this saturable absorption[4]. However, apart from SPA, there are also two-photon absorption (TPA) and free-carrier absorption (FCA) at high laser irradiance. TPA generates free electrons in conduction and free holes in valence whereas FCA promotes electrons into the higher conduction band and holes into the deeper valence band. We think TPA and FCA also have effect on the foundation of Q-switched pulses. In Ref. [8], we have given the coupled rate equations describing the operation of GaAs Q-switched lasers combining all these absorption processes and the two solutions of pulse profiles for SPA+TPA and SPA+TPA+FCA. As expected, the measured pulse profiles agreed with the simulated result. However, it should be noted that TPA follows the intensity, which results in pulse broadening because of the highest losses at the peak of the pulse, and FCA introduces high losses at the pulse trail and effectively shortens the pulse. All these results indicate that the explanation of Q-switching dynamics of GaAs by the saturable SPA, nonlinearity TPA and FCA processes is reasonable.

The laser is schematically shown in Fig. 1. A $3\times3\times5$ mm^3 Nd:YVO_4 laser rod which was 0.7 at.% Nd doped, is situated in a plane-plane laser cavity and end-pumped by a laser diode (OPC-DO15-PS), which provide a maximum pumping power of 15 W with a central wavelength of 808 nm. The rear sureface of the laser rod, coated for high transmission at 808 nm and high reflection at 1064 nm, acts as one of the resonator mirrors. A 0.5-mm-thick uncoated and undoped GaAs wafer oriented with its normal along the (100) crystal axis and optically polished on both faces is used as an output coupler. The GaAs is mounted in a metal mirror holder in order to remove the accumulated heat. In order to obtain the highest power density in the GaAs, a focusing lens with a focal length of 50 mm and an antireflection coating at 1064 nm on both surfaces are located in front of the GaAs wafer inside the 80-mm-long cavity. An LPE-1C power meter is used to measure the laser average power. An MRD500 PIN detector and a Tektronix oscilloscope TDS620B are used to receive and display the pulses. The energy of each pulse can be calculated from the laser average power and the pulse repetition rate.

By adjusting the position of the lens L, the highest power density in the GaAs and the greatest saturation can be realized and Q-switched pulses are readily observed. The spot sizes of the beam at the laser rod and GaAs wafer were 200 and 150 μm, respectively. At the pump power of 10 W, a stable fundamental-mode average power output of 2.11 W was obtained with a pulse duration of 140 ns, pulse energe of 76 μJ and pulse repetition rate of 28 kHz. The power conversion efficiency is ~21%.

Figure 2 shows a typical Q-switched laser pulse with an energy of 76 μJ and a pulse width of 140 ns. We can see that the Q-switched pulse shape is more symmetric than that of Q-switched pulse with dyes. This is because the free-carriers of GaAs have relatively long life-times (~100 ns)[10], and thus FCA will introduce high losses at the pulse trail and lead the pulse trail to fall off slightly more rapidly. Figures 3, 4 and 5 give the dependence of pulse duration, pulse repetition rate, pulse energy and average power on pump power, respectively. As we can seen from Fig. 3, the Q-switched pulse duration was reduced from 450 to 140 ns with the increase of the pumping power. The decrease in pulse duration was a result of the more rapid saturation of GaAs under high laser irradiance. From Fig. 4, we can see that the pulse repetition rate increases with pumping power when the

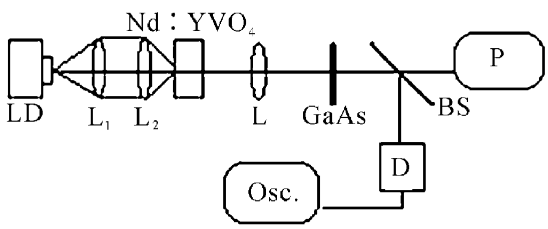

Fig. 1. The Schematic of the GaAs Q-switched Nd:YVO4 laser. LD: laser diode; L_1, L_2: optical coupling system; L: focusing lens; P: power meter; BS: beam splitter; D: detector; Osc: oscilloscope.

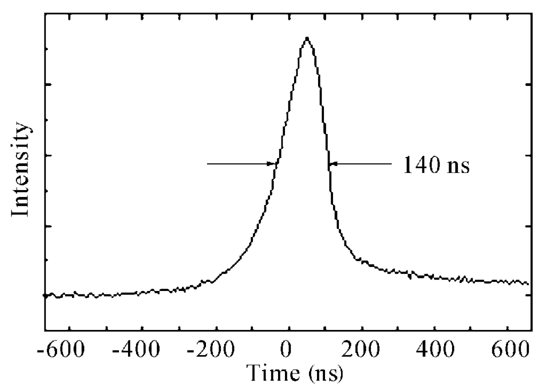

Fig. 2. Temporal profile of 140 ns, 76 μJ single Q-switched laser pulse.

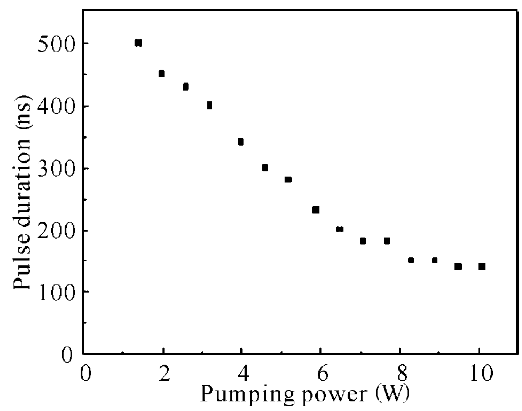

Fig. 3. The dependence of pulse duration on pump power.

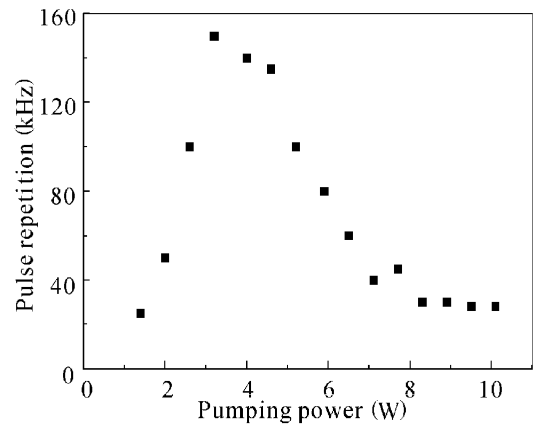

Fig. 4. The dependence of pulse repetition rate on pump power.

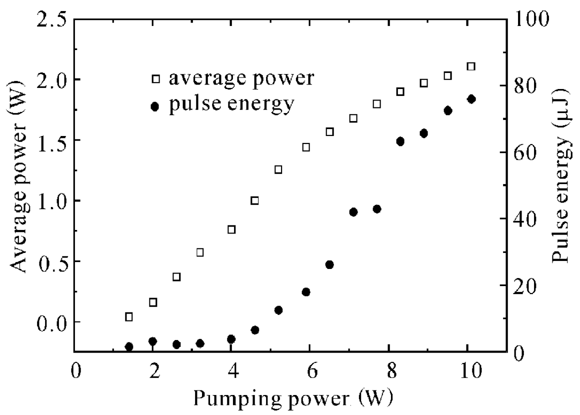

Fig. 5. Variation of pulse energy and average power with pump power.

pump power is slightly higher than the pump threshold, searches the maximum at about 4 W and then decreases from 200 kHz to 28 kHz. The observed decrease in repetition rate with increasing pump power is surprising and requires further research. The thermal effects may play an important role[4]. But we believe that TPA and FCA of GaAs may also play an important role. At sufficiently high intensity, TPA will dominate the interaction and then introduce high losses. On the other hand, the free-carrier density can become substantially larger than the density of electrons initially trapped at EL2 as a result of TPA, photoionization of EL2 and valence-to-$EL2^+$ transitions. The large number carriers, together with their relatively long lifetime, result in a strong intensity-dependent absorption loss of GaAs, which increases the threshold of the pulse generation. Thus it needs longer time to build up the initial population inversion density, consequently, the pulse repetition rate decreases.

The measured Q-switched pulses showed very stable. For 0.5-mm sample, we are able to reduce the jitter of pulse-to-pulse amplitude to better than 1% and the inter-pulse timing jitter less than 2% by careful adjusting the position of lens and GaAs wafer. The instability of the output power can be controlled within ±2%. In addition, our experiment comfirmed that the high damage threshold of the GaAs film of about several hundreds of mJ/cm^2 ensures a long time Q-switched operation of the laser without any surface damage of the film.

In conclusion, we demonstrate a passively Q-switching operation of a diode-pumped $Nd:YVO_4$ laser by using a GaAs wafer as the saturable absorber as well as the output coupler. The laser output characteristics are investigated. The laser provides Q-switched pulses with pulse duration 140 ns, average power 2.11 W, pulse repetition rate 28 kHz and pulse energy 76 μJ. The experimental results show that GaAs is an excellent passive Q-switch and has the advantages of simplicity and good thermal stability. Taking into account the availability of $Nd:YVO_4$ crystals with high quality, larger stimulated emission cross section and higher doping concentration, we believe that LD-pumped GaAs passively Q-switched $Nd:YVO_4$ lasers will be found wide applications in many fields.

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