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# Passively Q-switched Yb:YAG laser with a GaAs output coupler

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**Abstract**

By using GaAs as an output coupler as well as a saturable absorber, we demonstrated a diode-pumped passively Q-switched Yb:YAG laser at room temperature. At an incident pump power of 12.2 W, stable laser pulses of duration of 15.5 ns and energy of 75.6 μJ were generated at a repetition rate of 7.3 kHz. Effects of output coupling on the laser performance were investigated with a GaAs wafer that was coated with continuous variable reflectivity from 19.9–98.7%.


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*Keywords:* Diode-pumped; Passively Q-switched; Yb:YAG; GaAs

Passively Q-switched all-solid-state lasers employing solid-state saturable absorber are desirable for many applications such as micromachining, ranging, remote sensing, aid microsurgery. Compared with the active Q-switching, passive techniques can significantly simplify the operation, improve the efficiency, reliability and compactness, and reduce the cost of laser sources. To date, a variety of solid-state saturable absorb materials have been investigated, such as $LiF:F_2^-$ [1], tetravalent chromium-doped crystals [2–7], semiconductor saturable absorbers particularly those with the quantum-well structure [8–10]. Among the $Cr^{4+}$-doped crystals, $Cr^{4+}$:YAG is the most widely used saturable absorber for a variety of lasers because of its high damage threshold, large thermal conductivity and reliability. Semiconductor materials are attractive as saturable absorber because of the large optical non-linearity that can be obtained [11,12]. In addition, with the advent of bandgap engineering and modern semiconductor growth technology, parameters of a semiconductor saturable absorber, such as the absorption wavelength, recovery time and saturation energy, can be design and controlled at desired values [10].

Yb:YAG is an ideal laser medium for diode pumping. It has a broad absorption band-width of

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19 nm at 940 nm; Long radiative lifetime of 951 μs makes it very suitable for high peak power Q-switched pulse generation; Low quantum defect results in less thermal loading. Additionally, Yb:YAG has a broad emission spectrum, suitable for mode-locked operation to generate femtosecond pulses [13]. Passively Q-switched Yb:YAG lasers have been demonstrated recently by using semiconductor saturable absorber mirrors (SESAM) and $Cr^{4+}$:YAG as the Q-switch element [14,15]. Pulses with a few μJ energy were obtained. Bulk GaAs was first used for passive Q-switching by Kajava et al. for a diode-pumped Nd:YAG laser [16]. The energy of a photon at 1.06 μm is far below the GaAs band gap of 1.42 eV. The absorption at 1 μm is believed to be mainly due to the EL2 defect that forms deep donor levels about 0.82 eV below the band gap and two-photon absorption [17]. In this paper, we report on a diode-pumped passively Q-switched Yb:YAG laser with a single crystal GaAs wafer as both the saturable absorber and output coupler. At an incident pump power of 12.2 W, stable laser pulses of 75.6 μJ energy and 15.5 ns of duration were generated at a repetition rate of 7.3 kHz. We also investigated the effects of output coupling on the laser performance by using a GaAs wafer coated with a continuously variable reflectivity from 19.9–98.7%.

The experimental setup is shown schematically in Fig. 1. The pump source is a fiber bundle coupled laser-diode array which can provide a maximum CW output power of 15 W at a central wavelength of 940 nm. For pumping, the light from the fiber bundle end was collimated and focused using a commercially available optical reimaging unit to a spot size of approximately 400 μm in diameter. The 5-at.% Yb-doped

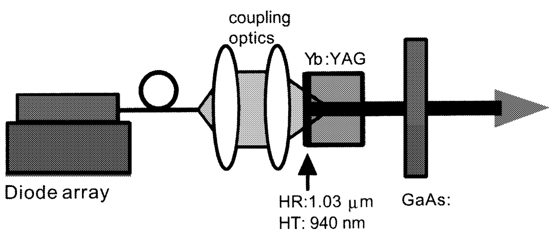


Fig. 1. Schematic diagram of the Yb:YAG laser passively Q-switched with a GaAs wafer as the saturable absorber and an output coupler.

Yb:YAG is 2 mm in thickness and has a diameter of 3 mm. One side of the laser crystal was anti-reflection coated at the pump wavelength of 940 nm ($R < 5\%$) and high-reflection coated at the fundamental wavelength of 1.03 μm ($R > 99.9\%$), which acts as a cavity mirror of the laser; the other side was anti-reflection coated at 1.03 μm to reduce the cavity loss and high-reflection coated at pump wavelength of 940 nm ($R > 90\%$) to improve the pump absorption. The laser crystal was wrapped with indium foil and mounted within a water cooled copper holder. High purity undoped GaAs wafers were $(100) \pm 0.3°$ cut and have a cross-section of 10 mm $\times$ 20 mm. Two GaAs samples were used in this experiment: one is a 625 μm thick uncoated wafer which was optically polished on both sides; another one has a thickness of 388 μm with one side anti-reflection coated. The other side was coated to have a continuously variable output transmission of 1.3–80.1% along the 20 mm direction. Thus the output transmission of the laser can be changed by simply translating the GaAs sample along the 20 mm edge direction. In order to remove the accumulated heat and prevent the heat-induced deformation on the output mirror, the GaAs wafers were mounted on a copper holder with an aperture of 5 mm $\times$ 18 mm. In passively Q-switched lasers, a short cavity-length is favorable for generation of short laser pulses. In this experiment, the cavity length used was about 15 mm which is limited by the crystal holder. The output of the pulsed Yb:YAG laser was monitored and analyzed by a Tektronix TDS360 digital oscilloscope and a fast photodiode.

The output characteristics of the Yb:YAG laser in CW operation was first measured using a conventional flat output coupler of $T = 8\%$. At 12.7 W incident pump power of an output power of 2.2 W was obtained at 1.03 μm. The slope efficiency was 31.5%. At the maximum pump power of 12.7 W, the fractional pump power that passed through the Yb:YAG crystal was measured to be about 9% even though there is a 90% HR coating on the second facet of the crystal. This suggests that the single-pass absorption of our 2 mm Yb:YAG crystal is not enough for pump powers of up to 12.7 W. Q-switched operation was achieved after that we replaced the conventional output coupler with a 625 μm thick uncoated GaAs wafer. The threshold of Q-switching was measured to be 8.9 W. At around threshold, the Q-switched pulses are unstable. With proper cavity alignment, stable pulses can be obtained when the pump power is higher than 9.1 W. Passively Q-switched lasers usually have a tendency to produce two or more sub-pulse that are different in pulse amplitude but repeat themselves periodically. However, we did not observe such sub-pulses even at the highest pump power of 12.2 W. This is probably because of the relatively large mode size on GaAS related with the piano-piano cavity design. The peak-to-peak intensity fluctuations and the interpulse time jittering at the maximum pump power were estimated to be <3 and <2%, respectively.

Fig. 2 shows the average output power and repetition rate as functions of the incident pump power. The average output power increases almost linearly with the incident pump power, no power saturation was observed at high pump power as in [16]. At a maximum incident pump power of 12.2 W, the Yb:YAG laser generated an average output power of 560 mW in the fundamental transverse mode. The beam-quality parameter $M^2$ and the beam radius on GaAs were measured to be $M^2 = 1.3$ and ~160 μm, respectively. The pulse repetition rate increased at first with the pump power from 3.0 to 15.3 kHz; after the pump power became greater than 11 W, it began to decrease. A repetition rate of 7.3 kHz was measured at 12.2 W pump power, the corresponding pulse energy was 75.6 μJ. At a pump power of 9.1 W, which is just above the threshold, the output pulse energy was 3.6 μJ. According to the measured beam radius on GaAs, the fluence inside the GaAs was estimated to be 7.6 mJ/cm$^2$. This fluence suggests a strong saturation of GaAs since the fluence at which saturation effects become important is 1.6 mJ/cm$^2$ [17] and strong saturation was believed to be realized at a fluence of 3.7 mJ/cm$^2$ [18]. The mechanism of the abnormal reduction in repetition rate shown in Fig. 2 is not very clear yet, it needs further investigation. We note that at the pump power of 11 W, where the repetition rate begins to decrease, the laser fluence inside the GaAs was 53.7 mJ/cm$^2$, which is much higher than that of the 7.6 mJ/cm$^2$ at around threshold. We believe that the abnormal reduction in repetition rate is probably related with some high-intensity-related absorptions such as two-photon absorption. Fig. 3 shows the pulse energy and pulse width (FWHM) as functions of the incident pump power. The pulse width was 66 ns near the threshold and decreased to 15.5 ns at the maximum incident pump power of 12.2 W. The highest peak power obtained was 4.9 kW. No damage was observed on GaAs after the laser was operated more than 1 h even at the highest pump power. Fig. 4 shows a typical Q-switched laser pulse with a duration of 15.5 ns.

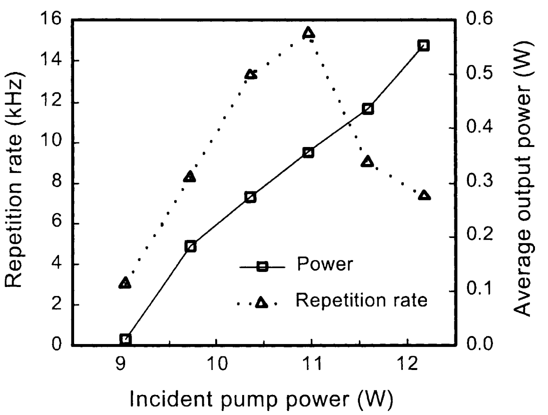


Fig. 2. Average output power and repetition rate vs incident pump power for the passively Q-switched Yb:YAG laser with a polished 625 μm GaAs as the saturable absorber as well as an output coupler.

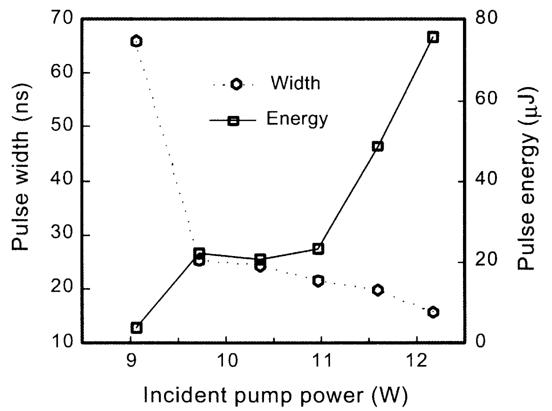


Fig. 3. Pulse width and pulse energy as functions of the incident pump power of the passively Q-switched Yb:YAG with a 625 μm GaAs.

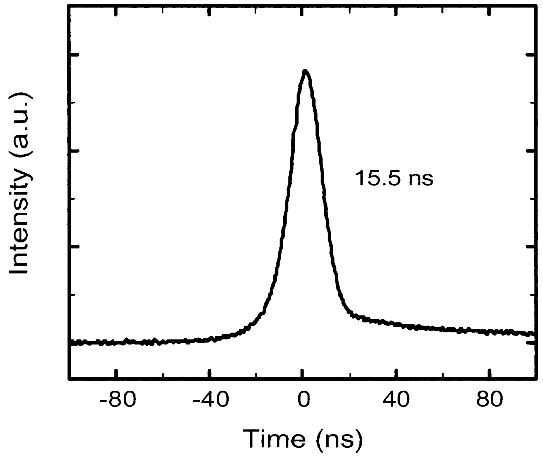


Fig. 4. Oscilloscope trace of a 15.5 ns pulse generated by a GaAs passively Q-switched Yb:YAG laser.

In general, GaAs wafers that used as intracavity saturable absorber elements have to be anti-reflection coated to reduce the cavity loss as each uncoated surface of GaAs wafer has a reflectivity of 30.6%. An uncoated GaAs wafer can be used as an output coupler because of the following two reasons. Firstly, GaAs has a high linear transmission at 1.03 μm because the photon energy at this wavelength is far below the GaAs band gap of 1.42 eV; secondly, the two uncoated surfaces form a Fabry–Perot (FP) cavity. The effective transmission at 1.03 μm of an uncoated GaAs output coupler was estimate to be 30% when it is fully saturated. Using an GaAs wafer as both the saturable absorber and output coupler can further simplify the laser design and make the laser more compact and reliable. Furthermore, the Fabry–Perot effect in the uncoated GaAs wafer can decrease the induced loss and increase the saturation intensity because the intensity within the FP cavity is smaller than the incident intensity.

We investigated the effects of output coupling on the performance of a GaAs passively Q-switched Yb:YAG laser by using a 388 μm GaAs wafer coated with continuously variable reflectivity from 19.9–98.7% along the 20 mm edge on one side. The other side of the wafer was anti-reflection coated at the oscillating wavelength. We chose a thin GaAs wafer in this measurement because an anti-reflection coated GaAs has no F–P effect and hence, will introduce higher loss than that of a FP mirror. The output coupling was changed by simply translating the GaAs wafer along the 20 mm edge direction. The incident pump power was 12 W and kept unchanged during the experiment. Dependencies of the average output power and pulse energy on the output transmission ($T$) are shown in Fig. 5. The laser cannot reach threshold due to the high output loss when $T$ was larger than 80%. In terms of the average output power, the optimum output transmission was $\sim 59\%$. The average output power decreased with the increase in output transmission when $T > 59\%$. The highest pulse energy of 50.5 μJ was obtained at an output transmission of 71% where the Q-switched pulses have the lowest repetition rate. Fig. 6 shows the variations of repetition rate and pulse duration with the output transmission. It is not surprising that the laser pulses have lower repetition rate at high $T$s. When the output transmission was smaller than 26.2%, however, the pulse repetition rate shows an abnormal reduction with the decrease of T. This repetition rate reduction behavior at high laser intensity is consistent with that shown in Fig. 2. It is interesting to note, for a output transmission of 26.2%, that the laser intensity within GaAs was estimated to be $\sim$51.1 mJ/cm$^2$, which is very close to the abnormal drop point of 53.7 mJ/cm$^2$ in Fig. 2. The coincidence in the two figures may suggest that a high-intensity-related absorption scheme takes effect at a high fluence of over

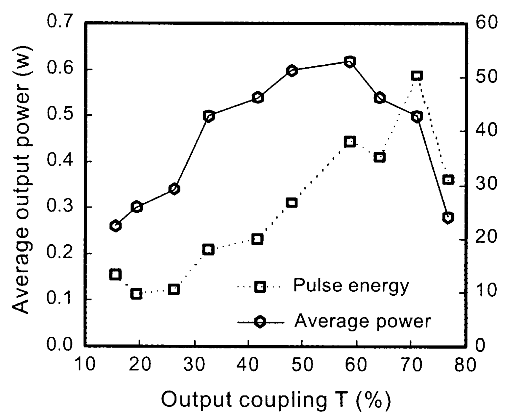


Fig. 5. Average output power and pulse energy as functions of the output transmission of the Yb:YAG laser passively Q-switched with a 388 μm GaAs wafer.

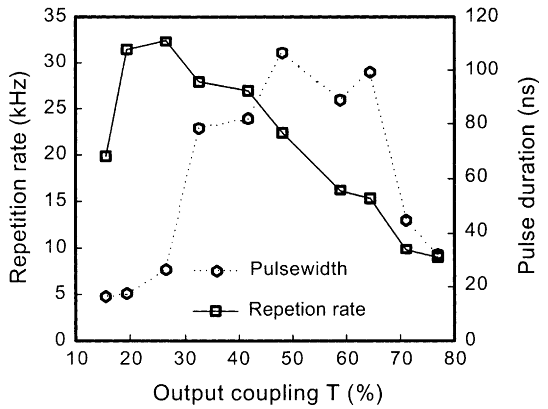


Fig. 6. Repetition rate and pulse width vs output transmission.

50 mJ/cm$^2$. Like the behavior of repetition rate, the pulse width also shows reduction when the output transmission was decreased to lower than 48%. The minimum pulse width of 16.2 ns was obtained at $T = 15.5\%$. The highest peak power of 1.1 kW was obtained at $T = 71\%$, where the output pulse width and energy are 44.5 ns and 50.5 μJ, respectively.

From Fig. 5 we can see that the pulse energy has a tendency to increase with the decrease in output transmission when $T < 20\%$ even though the average output power declined. The increase in pulse energy was caused by the reduction in repetition rate. In principle, the laser pulse energy and peak power could be further improved if we reduce the output coupling T to smaller than 15%. Unfortunately, efforts in further reducing $T$ and improve the pulse energy and peak power were hindered by the coating damage occurred at the second facet of Yb:YAG (the facet within the laser cavity and has an AR coating at 1.03 μm and a HR coating at 940 nm) due to the high intracavity intensity caused by the low output transmission. It is possible to further increase the pulse energy and peak power if the coating quality can be improved. It should be noted that no damage was observed on GaAs during the whole experiment, even when the coating damage occurred on the laser crystal.

In conclusion, we have demonstrated a diode-pumped passively Q-switched Yb:YAG laser using a single crystal GaAs wafer as both the saturable absorber and an output coupler. At an incident pump power of 12.2 W, stable laser pulses of duration of 15.5 ns and energy of 75.6 μJ were generated at a repetition rate of 7.3 kHz. We investigated the effects of output coupling on the laser performances with a 388 μm GaAs wafer that was coated with continuous variable reflectivity from 19.9–98.7%. The highest pulse energy and peak power of 50.5 μJ and 1.1 kW were obtained at an output transmission of $T = 71\%$.

## References


[1] J.A. Morris, C.R. Pollock, Opt. Lett. 15 (1990) 440.

[2] J.J. Zayhowski, C. Dill III, Opt. Lett. 19 (1994) 1427.

[3] M.I. Demchuk, V.P. Mikhailov, N.I. Zhavoronkov, N.V. Kuleshov, P.V. Prokohin, K.V. Yumashev, M.G. Livshits, B.I. Minkov, Opt. Lett. 17 (1992) 929.

[4] Y.K. Kuo, M.F. Huang, M. Birnbaum, IEEE J. Quantum Electron. 31 (1995) 657.

[5] W. Chen, K. Spariosu, Y.K. Kuo, M. Birnbaum, A.V. Shestakov, Opt. Comm. 104 (1993) 71.

[6] T. Kellner, F. Heine, G. Huber, S. Kück, Appl. Opt. 37 (1998) 7076.

[7] A. Agnesi, S. Dell'Acqua, C. Morello, G. Piccinno, G.C. Reali, Z. Sun, IEEE J. Sel. Top. Quantum Electron. 3 (1997) 45.

[8] G.J. Spühler, S. Reffert, M. Haiml, M. Moser, U. Keller, Appl. Phys. Lett. 78 (2001) 2733.

[9] U. Keller, K.J. Weingarten, X. Kärtner, D. Kopf, B. Braun, I.D. Jung, R. Fluck, C. Hönninger, N. Matuschek, J.A. er Au, IEEE J. Sel. Top. Quantum Electron. 2 (1996) 435.

[10] L.R. Brovelli, U. Keller, T.H. Chiu, J. Opt. Soc. Am. B 12 (1995) 311.

[11] Z. Zhang, L. Qian, D. Fan, X. Deng, Appl. Phys. Lett. 60 (1992) 419.

[12] A. Agnesi, A.D. Corno, P.O. Trapani, M. Fogliani, G.C. Reali, J.C. Diels, C.Y. Yeh, X.M. Zhao, V. Kubecek, IEEE J. Quantum Electron. 28 (1992) 710.

[13] C. Hönninger, G. Zhang, U. Keller, A. Giesen, Opt. Lett. 20 (1995) 2402.

[14] G.J. Spühler, R. Paschotta, M.P. Kullberg, M. Graf, M. Moser, E. Mix, G. Huber, C. Harder, U. Keller, Appl. Phys. B 72 (2001) 285.

[15] J. Dong, P. Deng, Y. Liu, Y. Zhang, J. Xu, W. Chen, X. Xie, Appl. Opt. 40 (2001) 4303.

[16] T.T. Kajava, A.L. Gaeta, Opt. Lett. 21 (1996) 1244.

[17] A.L. Smirl, G.C. Valley, K.M. Bohnert, T.F. Boggess Jr., IEEE J. Quantum Electron. 24 (1988) 289.

[18] G.Q. Gu, F. Zhou, G. Zhang, M.K. Chin, Electron. Lett. 34 (1998) 564.