Passive Q-switching of a Nd:YAG laser with a GaAs output coupler

Jianhui Gu
Feng Zhou
Siu Chung Tam, MEMBER SPIE
Wenjie Xie
Yee Loy Lam, MEMBER SPIE
Nanyang Technological University
School of Electrical and Electronic Engineering
Division of Microelectronics
Photonics Laboratory
Nanyang Avenue
Singapore 639798
E-mail: ejhgu@ntu.edu.sg

Yihong Chen
Gintic Institute of Manufacturing Technology
71 Nanyang Drive
Singapore 638075

Abstract. By using GaAs as an output coupler as well as a saturable absorber, passive Q-switching of an arc-lamp pumped Nd:YAG laser has been demonstrated. The shortest pulse duration obtained was 77.6 ns, corresponding to a pulse energy of 34 μJ. The laser average output power was 2.1 W with a power density in GaAs at 1.5×10^3 W cm^{-2}. No optical damage to GaAs was observed without any active cooling.

Subject terms: passive Q-switching; GaAs; saturable absorption; solid-state lasers.

Paper 990073 received Feb. 16, 1999; revised manuscript received June 30, 1999; accepted for publication July 13, 1999.

1 Introduction

Q-switching is required for many applications of solid-state lasers. Among a variety of different Q-switching techniques developed in the past, passive Q-switching has considerable advantages in terms of device simplicity, economy and overall efficiency. The generation of passively Q-switched laser pulses depends strongly on the availability of saturable absorbers. Intra-cavity passive elements such as LiF:F_2^-, Cr^{4+}:YSGG, Cr^{4+}:YAG, and Cr^{4+}:YSO bulk crystals, InGaAs/GaAs multiquantum well anti-resonant Fabry-Perot saturable absorbers (A-FPSA), and InGaAsP/InP semiconductor saturable absorber have been used for the passive Q-switching of solid state lasers.[1–6]

Bulk GaAs was first used as a nonlinear saturable absorber for the passive mode-locking of an arc-lamp pumped Nd:YAG laser.[7] Pulses as short as 10 ps with an energy of 10 μJ per pulse were reported. It has been reported recently that GaAs could be used to passively Q-switch a diode-pumped Nd:YAG laser with a pulse duration of 3 ns and a pulse energy of 13.2 μJ.[8] Although passive Q-switching is well understood, GaAs is a relatively new material for the passive Q-switching of solid-state lasers[9] and there are few papers discussing the laser performance. In this paper, we demonstrate the passive Q-switching of a Nd:YAG laser by simply using an uncoated GaAs wafer as the passive Q-switching element and laser output coupler. It is shown that this structure can be used for the Q-switching of an arc-lamp pumped Nd:YAG laser at an average power of more than 2 watts.

2 Experiment

The arc-lamp pumped Nd:YAG laser used for the experiment is shown in Fig. 1. The laser rod was 1 atm % Nd doped YAG with a dimension of $\phi 4\ \text{mm}\times 100\ \text{mm}$. Both ends of the laser rod were anti-reflection coated at the wavelength of 1064 nm. The laser cavity was 670 mm long, and was completed with a total reflection convex mirror with a radius curvature of -0.76 m and a GaAs output coupler. The output coupler is a piece of 628 μm thick uncoated single crystal GaAs plate. The high purity, high resistively undoped GaAs wafer is (100) $\pm 3°$ cut and optically polished on both facets. In order to remove the accumulated heat, the GaAs wafer was mounted onto a metal holder without any active cooling for the wafer and the holder. Apertures of different pinhole sizes were employed to select a TEM_{00} mode. A Tektronix TDS 544A oscilloscope with a bandwidth of 500 MHz and a Newport 818-BB-20 photon-detector with a rise time of 200 ps were employed to monitor the Q-switched pulses in the experiment.

When the cavity was properly aligned, the laser provided Q-switched pulses after the conventional flat glass output coupler was replaced by the GaAs plate. The pulse duration was about 10 μs at a repetition rate of 5.5 kHz. The laser beam power density on the GaAs wafer was only around 100 W cm^{-2} and the Q-switched pulses obtained had a slow rise time but fast fall time. Therefore, in order to sufficiently utilize the saturable absorption of GaAs, the laser beam power density in the GaAs wafer must be increased such that the non-linear absorption of GaAs becomes more effective. This was realized by introducing an intracavity lens to focus the beam onto the GaAs output coupler as shown in Fig. 1. The focusing lens used, with a

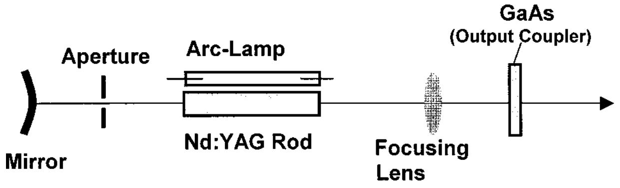

Fig. 1 Layout of the arc-lamp pumped Nd:YAG laser with a GaAs output coupler.

focal length of 50 mm and anti-reflection coating at 1.06 μm on both surfaces, was inserted into the cavity and its focal plane was located on the GaAs plate.

Under this condition, the output power was increased and the pulse duration was shortened greatly compared with those without a focusing lens. Fig. 2 shows the laser average output power as a function of the arc-lamp current. Being focused, the laser beam power density on the GaAs wafer reached $1.5\times10^3\,\mathrm{W\,cm^{-2}}$. We also measured the pulse duration and pulse repetition rate of the *Q*-switched pulses at different arc-lamp currents, and the results are shown in Fig. 3. The shortest pulse duration produced by this GaAs *Q*-switch was 77.6 ns at the current of 26 A (Fig. 4). The pulse repetition rate was from 20 kHz to 85 kHz when the arc-lamp current was increased from 20 A to 26 A, and then decreased to 55 kHz at 28 A. The pulse energy was from 8 μJ to 34 μJ with the increase in the arc-lamp current. In this experiment, the thermal effect of the laser rod would become significant if the pump current was too high. Hence we limited our pump current to 28 A.

Although some laser light was absorbed by GaAs, the temperature increase of the GaAs was small. Without any active cooling, the surface temperature of the GaAs was increased from the room temperature of 28.2°C to 32.4°C when the average output power was 2 W. No damage was observed for GaAs after the laser was operated for two hours at a pump current of 28 A. The measured beam divergence angle was approximately 11.7 mrad (full angle). This relatively large divergence angle was caused by the focusing of the laser beam before the GaAs wafer.

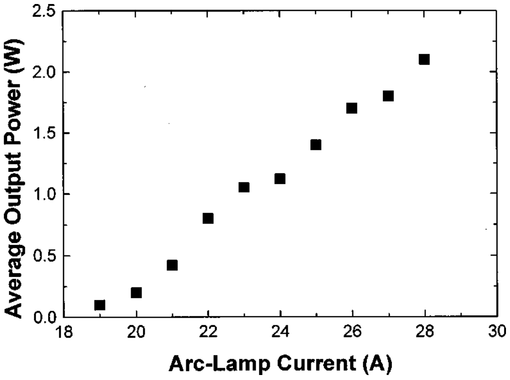

Fig. 2 *Q*-switched output average power as a function of the arc-lamp pump current.

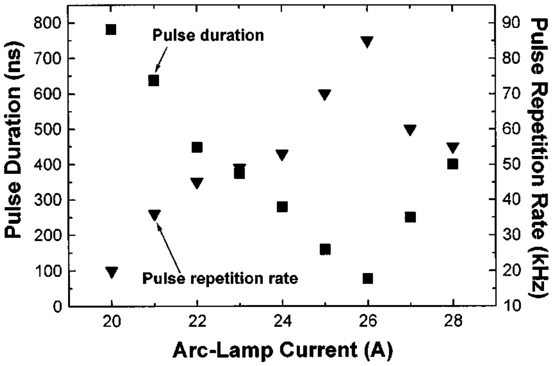

Fig. 3 Pulse duration and pulse repetition rate of the *Q*-switched pulses at different arc-lamp currents.

3 Simulation of the *Q*-Switched Pulse

Nonlinear absorption process in GaAs, i.e., the process of two-photon absorption (TPA) and free carrier absorption (FCA), affect *Q*-switching operation of the laser.[10,11] For a four-level laser system such as Nd:YAG, the rate equations can be expressed as

$$\frac{\mathrm{d}\phi}{\mathrm{d}t}=\frac{1}{\tau_R}[(2\sigma lN-\gamma-2\alpha l_q)\phi-Bl_q\phi^2] \tag{1}$$

$$\frac{\mathrm{d}N}{\mathrm{d}t}=-c\sigma N\phi-N/\tau+P(N_T-N) \tag{2}$$

where ϕ is the photon density ($\mathrm{cm^{-3}}$), N the population inversion density ($\mathrm{cm^{-3}}$), τ_R the cavity round-trip time (s), l and l_q the length of the laser rod and the thickness of the GaAs wafer respectively (cm), γ the linear loss of the cavity, α the saturable absorption of GaAs ($\mathrm{cm^{-1}}$), σ the stimulated emission cross section ($\mathrm{cm^2}$), c the velocity of light in vacuum ($\mathrm{cm\,s^{-1}}$), τ the spontaneous fluorescence lifetime (s), P the pump rate ($\mathrm{s^{-1}}$), N_T the total density of active atoms of the laser rod ($\mathrm{cm^{-3}}$), and B the coupling coefficient of TPA in GaAs ($\mathrm{cm^2}$), which is defined as[9]

$$B=6\beta h\nu c(\omega_0/\omega_q)^2 \tag{3}$$

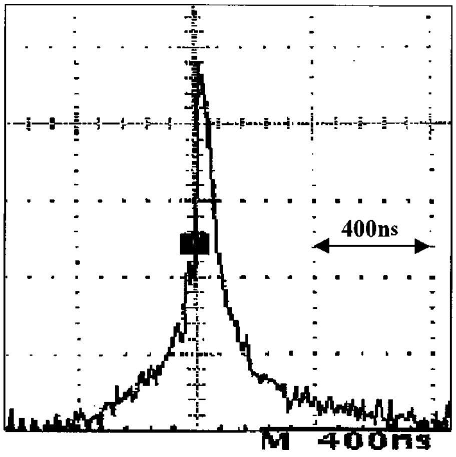

Fig. 4 The profile of a typical passive *Q*-switched pulse. Its duration is 77.6 ns with a repetition rate of 48.2 kHz when pumped at 26 A.

where β is the TPA coefficient $(\mathrm{cm\,W^{-1}})$, h the Planck's constant, ν the frequency of the laser beam (Hz), and ω_o and ω_q the spot sizes of the beam at the laser rod and GaAs wafer (cm). On the right-hand side of equation (1), the first term represents the increase of the photon density contributed by the stimulated emission of the population on the upper level, while the other terms represent the decrease of photon density caused by the linear cavity loss, absorption of GaAs and TPA. In equation (2), the first two terms on the right-hand side describe the population inversion consumption through stimulated emission and spontaneous emission of the upper level respectively, while the last term represents the population inversion supplied by optical pumping.

The saturable absorption coefficient α in equation (1) is strongly related to the power density of the lasing light. According to the energy-level model developed for energy transfer processes in GaAs by Valley and Smirl,[11] the level responsible for the absorption around 1 μm is believed to be the EL2 defect that forms a deep level 0.82 eV below the band edge. This level has a total density N_t (cm^{-3}), part of which (N^+) is positively charged. Transitions from the EL2 to the conduction band absorb optical energy and produce free electrons (n) with a rate of $\phi_q c(N_t-N^+)\sigma_e$, where $\phi_q=\phi(\omega_0/\omega_q)^2$ is the photon density at the GaAs wafer (cm^{-3}) and σ_e is the cross section of EL2 absorption (cm^2). Valence to EL2$^+$ transitions produce free holes (p) and the neutral EL2 donors from EL2$^+$ with a rate of $\phi_q c N^+\sigma_h$, where σ_h is the cross section of EL2$^+$ absorption (cm^2). TPA generates free electrons and holes with a rate of $Bc\phi_q^2/12$, whereas FCA promotes electrons higher into the conduction band and holes deeper into the valence band. Combining all these effects with the accompanying recombination processes, the following intracavity rate equations can be derived for GaAs:[8,11]

$$\frac{\mathrm{d}n}{\mathrm{d}t}=\phi_q c(N_t-N^+)\sigma_e+Bc\phi_q^2/12-\gamma_{et}nN^+-\gamma_{eh}np \tag{4}$$

$$\frac{\mathrm{d}p}{\mathrm{d}t}=\phi_q cN^+\sigma_h+Bc\phi_q^2/12-\gamma_{hd}p(N_t-N^+)-\gamma_{eh}np \tag{5}$$

$$\begin{aligned}\frac{\mathrm{d}N^+}{\mathrm{d}t}&=\phi_q c[(N_t-N^+)\sigma_e+N^+\sigma_h]\\&\quad-\gamma_{et}nN^+ +\gamma_{hd}p(N_t-N^+)\end{aligned} \tag{6}$$

where γ_{et}, γ_{hd} and γ_{eh} are the recombination coefficients of electron-EL2, hole-EL2 and direct electron-hole respectively $(\mathrm{cm^3\,s^{-1}})$ and N^+ the portion of charged density of EL2 level (cm^{-3}). The absorption coefficient α can be expressed as

$$\alpha=\sigma_e(N_t-N^+)+\sigma_h N^+ +\sigma_{fc}n \tag{7}$$

where σ_{fc} is the FCA cross section (cm^2). It is noticed that the photon density and the absorption coefficient can be obtained by simultaneously solving the above equations (1) to (7).

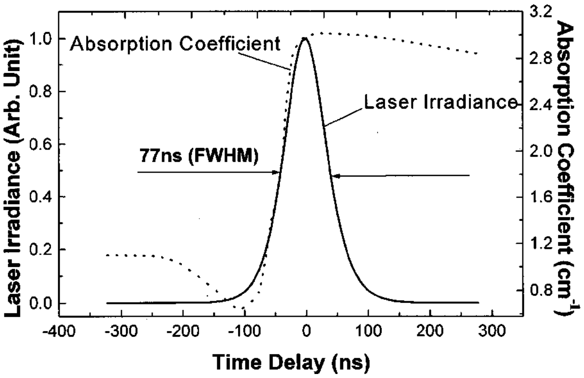

Fig. 5 Simulated absorption coefficient of the GaAs and the *Q*-switched laser pulse profile.

According to the laser specifications and parameters of GaAs, we have simulated the *Q*-switched pulse profile and the absorption coefficient of GaAs. For a set of appropriate initial values of ϕ, N, n, p, and N^+ as $1\times10^{-4}\,\mathrm{cm}^{-3}$, $4.6\times10^{17}\,\mathrm{cm}^{-3}$, 0.0, 0.0 and $1.4\times10^{15}\,\mathrm{cm}^{-3}$ respectively,[9] we obtained the simulated photon density and the absorption coefficient as shown in Fig. 5. The simulated pulse duration of 77 ns is in a good agreement with the measured result of 77.6 ns. The pulse shape is nearly symmetrical and similar to the measured pulse shown in Fig. 4. It can be seen from Fig. 5 that, under the irradiation of laser beam, the absorption coefficient of GaAs begins to decrease from the initial value, i.e., its linear absorption coefficient of $1.1\,\mathrm{cm}^{-1}$, nearly the same as the value provided in Ref. 8, to the saturated value of about $0.7\,\mathrm{cm}^{-1}$. But there is no lasing yet because of the high cavity loss. Once the GaAs is saturated, the Q value of the cavity is increased rapidly, and thus a short *Q*-switched pulse is generated.

The increase of the absorption coefficient is due to both the TPA, which scales with the photon density, and FCA, which increases with the generated electron density. The life time of free carriers in undoped GaAs is on the order of 10^3 ns [Ref 12]. Consequently, free carrier absorption is still relatively strong following development of the pulse peak. The long carrier life time also leads to increased FCA which results in a pulse stretching. The trailing edge of the pulse suffers higher losses than the leading edge, which makes the falling of the trailing edge faster than the rising of the leading edge. This phenomenon was observed frequently in the experiment, especially with high pumping rates. It is expected to shorten the pulse duration by this mechanism in the GaAs *Q*-switching.

4 Conclusion

To the best of our knowledge, this is the first demonstration of using uncoated and undoped GaAs wafer as an output coupler as well as a saturable absorber to passively *Q*-switch an arc-lamp pumped Nd:YAG laser. The laser produced stable passively *Q*-switched pulses with a duration of 77.6 ns at an average output power of 2.1 W. The simulated pulse duration and the pulse profile agree with the measurement. The pulse duration of the *Q*-switched pulses decreases with the increase in arc-lamp pump power.

However, when the pump power was too high, multi-pulses occurred for the GaAs Q-switching. This led to an instability and broadening of the output pulses. This situation could be avoided in practical applications by optimizing the pumping rate and the power density in GaAs wafer.

We did not observe any optical damage to the GaAs wafer in the experiments, in which the maximum power density reached 1.5×10^3 W cm^{-2}. The temperature rise in the GaAs wafer was less than 4.5°C for a continuous operation of two hours since the heat in the GaAs could be dissipated to the metal holder of the output coupler. Therefore, we suppose that the system could be scaled to a higher power level. Compared with the A-O Q-switching operation of the same Nd:YAG laser, nearly the same pulse durations were obtained under the same operating conditions. GaAs Q-switching, however, has the advantages of low cost and simplicity, especially for diode-pumped solid state lasers by combining the Q-switch element and output coupler together with a single GaAs plate.

References

1. J. A. Morris and C. R. Pollock, ''Passive Q-switching of a diode-pumped Nd:YAG laser with a saturable absorber,'' *Opt. Lett.* **15**, 440–442 (1990).
2. I. V. Klimov, N. Y. Nikol'skill, V. B. Tsvetkov and I. A. Shcherbakov, ''Passive Q-switching of pulsed Nd^{3+} lasers using Cr^{4+}:YSGG switches exhibiting phototropic properties,'' *Sov. J. Quantum Electron.* **22**, 653–656 (1992).
3. A. Agnesi, S. Dell'Acqua, G. C. Keali and Z. Sun, ''High performance Gr^{4+}:YAG Q-switched CW diode-pumped Nd:YAG laser,'' *Opt. Quantum Electron.* **29**, 429–433 (1997).
4. Y. K. Kuo, M. F. Huang and M. Birnbaum, ''Tunable Cr^{4+}:YSO Q-switched Cr:LiCAF laser,'' *IEEE J. Quantum Electron.* **31**(4), 657–663 (1995).
5. B. Braun and U. Keller, ''Single-frequency Q-switched ring laser with an antiresonant Fabry-Perot saturable absorber,'' *Opt. Lett.* **20**(19), 1020–1022 (1996).
6. F. Fluck, B. Braun, E. Gini, H. Melchior and U. Keller, ''Passively Q-switched 1.34 μm Nd:YVO$_4$ microchip laser with semiconductor saturable-absorber mirrors,'' *Opt. Lett.* **22**(13), 991–993 (1997).
7. Z. Zhang, L. Qian, D. Fan and X. Deng, ''Gallium arsenide: A new material to accomplish passively mode-locked Nd:YAG laser,'' *Appl. Phys. Lett.* **60**, 419–421 (1992).
8. T. T. Kajava and L. G. Alexander, ''Q-switching of a diode-pumped Nd:YAG laser with GaAs,'' *Opt. Lett.* **21**(16), 1244–1246 (1996).
9. T. T. Kajava and L. G. Alexander, ''Intra-cavity frequency-doubling of Nd:YAG laser passively Q-switched with GaAs,'' *Opt. Commun.* **137**, 93–97 (1997).
10. A. Agnesi, A. D. Corno, P. D. Trapani, et al., ''Generation of extended pulse trains of minimum duration by passive negative feedback applied to solid-state Q-switched lasers,'' *IEEE J. Quantum Electron.* **28**(3), 710–718 (1992).
11. G. C. Valley and A. L. Smirl, ''Theory of transient energy transfer in gallium arsenide,'' *IEEE J. Quantum Electron.* **24**(2), 304–310 (1988).
12. A. R. Adams, ''Properties of Gallium Arsenide,'' Chapter 5 and Chapter 6, Wiley & Sons, New York, 1986.

Jianhui Gu received his BEng and MSci degrees in opto-electronics engineering from Huazhong University of Science and Technology in 1986 and 1989, respectively. From 1989 to 1998, he worked in National Laboratory of Laser Technology, Huazhong University of Science and Technology, China, and researched on high-power laser systems and the interaction between high-power laser beam and various materials. From 1998, he was at Nanyang Technological University as a PhD candidate and researched on high-power DPSS lasers and applications.

Feng Zhou received his BSc degree from Zhejiang University, China, in 1983, MSc and PhD degrees from Shanghai Institute of Optics and Fine Mechanics, Academia Sinica, in 1986 and in 1989, respectively. Currently he is a staff scientist at NZ Applied Technologies. Prior to joining NZAT, he was a post-doctoral research fellow at Strathclyde University, Glasgow University, Imperial College in the United Kingdom, and a lecturer in Nanyang Technological University, Singapore. His research interests are diode-pumped solid-state lasers, ultrashort pulse generation and amplification, integrated optical devices, and optical sensors.

Siu Chung Tam obtained his PhD degree in optics from Imperial College, London, in 1983. Prior to his postgraduate studies, he worked for five years in Hong Kong as a manufacturing engineer. Since 1983, he has been teaching in the Nanyang Technological University, Singapore. He is currently an associate professor in the School of Electrical and Electronic Engineering. His areas of research and teaching are in optical engineering, laser engineering, and quality engineering. He is a member of SPIE and many other professional institutions, and has published more than 50 papers in refereed journals and international conferences. He is also a cofounder of DataMark Technologies Pte Ltd, a spin-off company from NTU, that was set up in 1998.

Wenjie Xie received his BS in optoelectronics engineering from Beijing Institute of Technology in 1991 and MS in optoelectronics engineering from Institute of Electronics, Chinese Academy of Sciences, in 1996. Before studying in Nanyang Technological University, Singapore, he worked in Institute of Electronics, Chinese Academy of Sciences as a research engineer. His research interests are in diode pumped solid state lasers, and gas laser systems.

Yee Loy Lam received his BEng and MSc from the National University of Singapore in 1985 and 1987, respectively, and his MSE and PhD from the University of Michigan in 1992 and 1993, respectively. From 1985 to 1990, he was a system engineer and then manager in Rank O'Connor's (S) Pte Ltd, developing and manufacturing building automation systems. Thereafter, he joined the School of Electrical and Electronics Engineering in Nanyang Technological University, Singapore, where he is presently an associate professor and head of the Division of Microelectronics in the school. Dr. Lam is a member of IEEE and SPIE. His research interests include optoelectronics, sol-gel photonics, fiber-optic sensors, lasers, and optical networking.

Yihong Chen received his BE and MSci degrees in laser technology from Huazhong University of Science and Technology in 1983 and 1986 respectively and his PhD degree from Nanyang Technological University of Singapore in 1998. He worked at National Laboratory for Laser Technology of China from 1986 to 1994, and has been with Gintic Institute of Manufacturing Technology since June 1994. His research focuses on lasers and laser material processing.