Passive Q-switching with GaAs or Bi-doped GaAs saturable absorber in Tm:LuAG laser operating at 2μm wavelength

Lin Wu, Dechun Li, Shengzhi Zhao, Kejian Yang, Xiangyang Li, Reng Wang, and Ji Liu

1School of Information Science and Engineering, Shandong University, Jinan, 250100, China
2Shanghai Institute of Technical Physics, Chinese Academy of Sciences, Shanghai 200083, China

dechun@sdu.edu.cn

Abstract: We report the first demonstration of a diode pumped passively Q-switched Tm:LuAG laser near 2μm wavelength with Bi-doped or undoped GaAs wafer as saturable absorber. For Bi-doped GaAs saturable absorber, stable Q-switched pulses with duration of 63.3ns under a repetition rate of 132.7 kHz and pulse energy of 5.51μJ are generated. In comparison to the passively Q-switched laser with undoped GaAs saturable absorber, the laser with Bi-doped GaAs can produce shorter pulses and higher peak power at almost the same incident pump power. The results suggest that Bi-doped GaAs can be an attractive candidate of saturable absorber for Q-switched laser near 2μm wavelength.

References and links

1. S. W. Henderson, C. P. Hale, J. R. Magee, M. J. Kavaya, and A. V. Huffaker, “Eye-safe coherent laser radar system at 2.1 μm using Tm, Ho:YAG lasers,” Opt. Lett. 16(10), 773–775 (1991).
2. N. Leindecker, A. Marandi, R. L. Byer, K. L. Vodopyanov, J. Jiang, I. Hartl, M. Fermann, and P. G. Schunemann, “Octave-spanning ultrafast OPO with 2.6-6.1 μm instantaneous bandwidth pumped by femtosecond Tm-fiber laser,” Opt. Express 20(7), 7046–7053 (2012).
3. A. V. Podlipensky, V. G. Shcherbitsky, N. V. Kuleshov, V. I. Levenchenko, V. N. Yakimovich, M. Mond, E. Heumann, G. Huber, H. Kretschmann, and S. Kück, “Efficient laser operation and continuous-wave diode pumping of Cr2+:ZnSe single crystals,” Appl. Phys. B 72(2), 253–255 (2001).
4. J. D. Kmetec, T. S. Kubo, T. J. Kane, and C. J. Grund, “Laser performance of diode-pumped thulium-doped Y3Al5O12, (Y, Lu)3Al5O12, and Lu3Al5O12 crystals,” Opt. Lett. 19(3), 186 (1994).
5. P. Koopmann, S. Lamrini, K. Scholle, P. Fuhrberg, K. Petermann, and G. Huber, “Efficient diode-pumped laser operation of Tm:Lu2O3 around 2 μm,” Opt. Lett. 36(6), 948–950 (2011).
6. N. P. Barnes, M. G. Jani, and R. L. Hutcheson, “Diode-pumped, room-temperature Tm:LuAG laser,” Appl. Opt. 34(21), 4290–4294 (1995).
7. L. Wang, C. Gao, M. Gao, L. Liu, and F. Yue, “Diode-pumped 2 μm tunable single-frequency Tm:LuAG laser with intra cavity etalons,” Appl. Opt. 52(12), 1272–1275 (2013).
8. Y. Bai, N. Wu, J. Zhang, J. Li, S. Li, J. Xu, and P. Deng, “Passively Q-switched Nd:YVO4(4) laser with a Cr4+:YAG crystal saturable absorber,” Appl. Opt. 36(12), 2468–2472 (1997).
9. A. Agnesi, S. Dell’Acqua, C. Morello, G. Piccinno, G. C. Reali, and Z. Sun, “Diode-Pumped Neodymium Lasers Repetitively Q-Switched by Cr4+:YAG Solid-State Saturable Absorbers,” IEEE J. Quantum Electron. 31(1), 45–52 (1995).
10. T. L. Feng, S. Z. Zhao, K. J. Yang, Q. Li, D. C. Li, J. Zhao, W. C. Qiao, J. Hou, Y. Yang, J. L. He, L. H. Zheng, Q. G. Wang, X. D. Xu, L. B. Su, and J. Xu, “Diode-pumped continuous wave tunable and graphene Q-switched Tm:LSO lasers,” Opt. Express 21(21), 24665–24673 (2013).
11. J. Liu, Y. Wang, Z. Qu, and X. Fan, “2μm passive Q-switched mode-locked Tm3+:YAP laser with single-walled carbon nanotube absorber,” Opt. Laser Technol. 44(4), 960–962 (2012).
12. F. Z. Qamar and T. A. King, “Passive Q-switching of the Tm-silica fibre laser near 2μm by a Cr2+:ZnSe saturable absorber crystal,” Opt. Commun. 248(4–6), 501–508 (2005).
13. Y. Yao, Y. Tian, G. Li, and Y. Wang, “InGaAs/GaAs saturable absorber for diode-pumped passively Q-switched dual-wavelength Tm:YAP lasers,” Opt. Express 18(13), 13574–13579 (2010).
14. M. S. Gaponenko, A. M. Malysarevich, K. V. Yumashev, H. Raaben, A. A. Zhlin, and A. A. Lipovskii, “Holmium lasers passively Q-switched with PbS quantum-dot-doped glasses,” Appl. Opt. 45(3), 536–539 (2006).
1. Introduction

Diode-pumped solid-state lasers based on Tm$^{3+}$ ions emitting in 2µm wavelength region have attracted much interest for their various applications in medicine, laser ranging, time-resolved molecular spectroscopy, detection LIDAR, optical communication, as well as pumping sources for optical parametric oscillators (OPOs) [1–3]. As a prominent host material for Tm$^{3+}$ ions doping, Tm:LuAG crystal possesses excellent physical and chemical properties, as well as a good thermal conductivity [4, 5]. Until now, the reports on Tm:LuAG lasers have mainly focused on CW and wavelength tunable operations [6, 7]. Additionally, passive Q-switching methods provide efficient and simple ways to generate pulses with much higher energy. Saturable absorber based passive Q-switching has advantages of compactness, simplicity and reliability [8, 9]. For passively Q-switched 2µm laser, lots of materials have been employed as saturable absorbers such as graphene [10], carbon nanotubes [11], Cr:ZnS, Cr:ZnSe [12], InGaAs/GaAs [13], PbS-doped glass [14], and etc.

In recent years, GaAs has been widely used in passively mode-locked and Q-switched Nd$^{3+}$ or Yb$^{3+}$ doped solid-state lasers around 1µm wavelength, due to its thermal stabilities and large optical nonlinearities [15–18]. At 1µm wavelength range, the energy of a photon at 1.06 µm wavelength is far below the GaAs band gap of 1.42 eV, and the absorption is believed to be mainly due to the EL2 defect, which forms deep donor levels about 0.82 eV below the band gap. Apart from that, the nonlinear absorption of GaAs is also dominated by two-photon absorption (TPA) at high laser irradiance [19]. For 2µm wavelength range, the energy of a photon is much lower, however, there are still many other kinds of defects in GaAs semiconductor material, which may contribute to the nonlinear absorption at 2µm wavelength. Therefore, it is necessary to study the performance of GaAs as a saturable absorber used in passively Q-switched 2µm laser.

On the other hand, bismuth doping is an effective way to modify the electronic and optical properties of GaAs. Theoretical calculations on the effects of Bismuth doping in GaAs saturable absorber have been reported previously [20]. A passively Q-switched Nd:GGG laser with a minimum pulse duration of 1.2ns and a passively Q-switched and mode-locked Nd:GGG laser have been realized by using Bi-doped GaAs saturable absorber [21, 22].

In this paper, we present the performance of 2µm Tm:LuAG laser with Bi-doped GaAs or undoped GaAs saturable absorber for the first time. For comparison, the Q-switched Tm:LuAG laser with Bi-doped GaAs or undoped GaAs saturable absorber is achieved under the same conditions.
2. Experimental setup

A schematic diagram of the experimental set-up is shown in Fig. 1. The used Tm:LuAG crystal with dimensions of $4 \times 4 \times 8 \text{ mm}^3$ was grown by the Czochralski technique and has a Tm-doped concentration of 5%. Both surfaces of the crystal were antireflection coated at 750-850 nm (reflectivity < 2%) and 1830-2230 nm (reflectivity < 0.8%). The employed pump source was a fiber-coupled diode laser with the fiber core size of 100 $\mu$m whose emission wavelength is around 789 nm. The pump light was focused by a 1:1 imaging module, Tm:LuAG crystal was pumped with a spot diameter of 100 $\mu$m. Tm:LuAG crystal was wrapped in indium foil and mounted in a copper block cooled at 13°C with water. The whole length of the oscillating cavity was kept as 2.5 cm. M1 was a concave mirror (R = $-200 \text{ mm}$) which was antireflection coated from 750 to 850 nm (reflectivity < 2%) and high reflectivity coated (reflectivity > 99.9%) from 1850 to 2100 nm. M2 was a flat mirror working as output coupler (OC) with 5% transmissions at 2 $\mu$m. A piece of Bi-doped GaAs (or undoped GaAs) was then placed very close to the output coupler. To remove the leaking pump light, a filter was placed behind the mirror M2. A MAX 500AD laser power meter (Coherent Inc., USA) and a DPO 7104C digital phosphor oscilloscope (1 GHz bandwidth and 20 GS/s sampling rate, Tektronix Inc., USA) were used to measure the yield power and the pulse characteristics of the laser, respectively.

![Fig. 1. The schematic of passively Q-switched Tm:LuAG laser.](image)

![Fig. 2. The absorption spectrum of Bi-doped GaAs (without annealing and annealed at 700°C).](image)

The Bi-doped GaAs and undoped GaAs samples used in the experiment are both on the (100) orientation, and have the same thickness of 600 $\mu$m and the size of 26 mm $\times$ 26 mm. Bismuth was doped into GaAs using ion bombardment at 500 keV with a dose of $1 \times 10^{14}$ ions/cm$^2$. The thickness of the implantation layer is about 100 nm. Samples were subsequently annealed in a rapid thermal annealing system in nitrogen ambient. The Bi-doped GaAs used...
in this experiment was annealed at 700°C and the annealing duration was fixed at 60s. It has been proved that annealing could be an efficient way to eliminate lattice damage and activate implants while minimizing impurity diffusion [23, 24]. In our experiment, the Bi-doped GaAs samples are uncoated in order to avoid the structural damage of the ion-implanted layer during the coating procedure. Therefore, the undoped GaAs samples are uncoated to keep the same with the Bi-doped GaAs. When used as saturable absorbers during Q-switching operation, the Bi-doped GaAs and GaAs were vertically inserted in the cavity, placed very close to the output coupler, and aligned precisely for loss minimization.

The absorption spectrum of Bi-doped GaAs samples was obtained by infrared spectrometer, and the profile is demonstrated in Fig. 2. It can be seen that at 2μm wavelength, the absorption of the Bi-doped GaAs sample annealed at 700°C is obviously higher than the absorption of the sample without annealing. The absorption of Bi-doped GaAs annealed at 700°C around 2μm wavelength is about 51.8%. Furthermore, in our experiment, an acousto-optic(AO) Q-switched Tm:LuAG laser with a pulse duration of about 350ns at a repetition rate of 1 kHz is used to measure the nonlinear characteristics of the Bi-doped GaAs and undoped GaAs samples. The nonlinear transmission versus the incident pulse fluence is shown in Fig. 3. From Fig. 3(a), it can be seen that the saturation starts at incident pulse fluence of 14.1mJ/cm² for Bi-doped GaAs, and the modulation depth, the nonsaturable loss of the sample are about 4% and 40.8%, respectively. Meanwhile, from Fig. 3(b), it is found that the saturation starts at pulse fluence of 8.1mJ/cm² for undoped GaAs, the modulation depth and nonsaturable loss are about 5% and 42.1%. In addition, the estimated saturation fluences for GaAs and Bi-doped GaAs are lower when compared with the case of Cr:ZnSe, and higher than the saturation fluence of the SWCNT and graphene [12, 25].

![Fig. 3. The nonlinear transmission versus incident pulse fluence. (a) The nonlinear transmission of Bi-doped GaAs sample. (b) The nonlinear transmission of undoped GaAs sample.](image)

3. Experimental results

The continuous wave (CW) Tm:LuAG laser was investigated firstly. The output light of the laser is circularly polarized light because the Tm:LuAG is an isotropy crystal. The threshold pump power of the CW Tm:LuAG laser is found to be 1.2W. A maximum average output power of 1.46W was obtained under the pump power of 6.7W, and the slope efficiency is about 27.8%. The average output power versus incident pump power is shown in Fig. 4. With the Bi-doped GaAs and undoped GaAs inserted into the resonator cavity, stable Q-switching operation was achieved by aligning the cavity mirrors carefully. The threshold pump powers for passive Q-switching operations are both around 1.2W. Stable passive Q-switching operation could be achieved as soon as the pump powers reached the oscillation thresholds. With the incident pump power increases from 1.5W to 6.7W, the output power of the Bi-
doped GaAs and undoped GaAs Q-switched lasers both increased rapidly. The maximum average output powers of 0.73 W and 0.8 W are achieved by using Bi-doped and undoped GaAs, corresponding to slope efficiencies of 13.9% and 15.1%, respectively.

![Graph](https://via.placeholder.com/150)

**Fig. 4.** Average output power versus incident pump power.

Figure 5 and Fig. 6 give the dependences of the pulse duration and the pulse repetition rate on the incident pump power. From Fig. 5, we can see that the Bi-doped GaAs Q-switched pulse width is much shorter than that of the undoped GaAs Q-switched one at each pump power, decreased from 700 to 63 ns with the increasing pump power. For the laser with undoped GaAs saturable absorber, the pulse duration decreased from 930 to 264 ns with the increasing incident pump power. From Fig. 6, it can be seen that the pulse repetition rate of undoped GaAs Q-switched laser increased from 25.6 to 114.1 kHz. But for Bi-doped GaAs Q-switched laser, it can produce higher pulse repetition rate at each pump power, and the highest pulse repetition rate of 132.7 kHz is achieved at the incident pump power of 6.7 W. Additionally, for Bi-doped GaAs or undoped GaAs Q-switched laser, the obtained pulse duration is the most shortest one when compared to the other 2μm saturable absorbers, such as CNT, graphene and Cr:ZnSe. The obtained pulse repetition rate of the Bi-doped GaAs or undoped GaAs Q-switched laser is much higher than the graphene saturable absorber and Cr:ZnSe, but smaller than the SWCNT.
Figure 5 shows the single pulse energy and the peak power relate to the incident pump power. From Fig. 7(a), we can see that with the increase of the pump power, the peak power of the Q-switched lasers with undoped GaAs and Bi-doped GaAs both increase monotonously, and the peak power of Bi-doped GaAs Q-switched laser is much higher than the undoped GaAs Q-switched laser at each pump power. At an incident pump power of 6.7 W, a maximum peak power of 26.5 W is achieved by the Q-switched laser with undoped GaAs, and for Bi-doped GaAs Q-switched laser, the highest peak power of 87.5 W is obtained with the pump power of 6.7 W. On the other hand, the single pulse energy of the Q-switched lasers versus the pump power is given in Fig. 7(b). It is shown that with the increasing of pump power from 2.4 W to 4.9 W, the single pulse energy of the two different Q-switched lasers increases obviously. As for the inflexion point observed in the single pulse energy variation tendency, the thermally induced losses in the laser crystal and saturable absorber are regarded as the possible reason. At each pump power, the single pulse energy of undoped GaAs Q-switched laser is a little higher than that of Bi-doped GaAs Q-switched laser.
The profiles of Q-switched pulses are shown in Fig. 8. It can be seen that the Bi-doped GaAs Q-switched laser can produce much shorter pulse duration under the same conditions compared to undoped GaAs Q-switched laser. At the incident pump power of 6.7W, the pulse durations of Q-switched laser with undoped GaAs or Bi-doped GaAs are 264ns and 63.3ns, respectively. The small background level of the oscilloscope trace of the Bi-doped GaAs Q-switched laser is speculated to be caused by the optical noise of experiment environment. Figure 9 gives the pulse trains of the Q-switched laser with undoped GaAs or Bi-doped GaAs. Small DC level of pulse trains in Fig. 9 may be caused by the dark current of the photodiode detector and the optical noise of background. The temporal Q-switched pulse train oscilloscope profile of passively undoped GaAs Q-switched Tm:LuAG laser at pulse repetition rate of 43.9kHz is shown in Fig. 9(a), which indicated stable Q-switching operation is achieved. Similarly, profile of passively Bi-doped GaAs Q-switched Tm:LuAG laser at pulse repetition rate of 127.4kHz is shown in Fig. 9(b). During the passively Q-switching operation, the TEM$_{00}$ Gaussian mode radius inside the used Bi-doped GaAs wafer is calculated to be about 150μm using ABCD matrix theory. At the pump power at 6.7W, the energy of the pulse in the cavity is about 107.5μJ. According to that, the fluence inside the GaAs can be estimated to be 152.1mJ/cm$^2$, suggesting that the Bi-doped GaAs is strongly saturated. From all the results above, we speculate that the Bi-doping does little harm to the performance as saturable absorber. And the results observed in our experiments suggesting that Bi-doping can better the pulse characteristics of the laser compared with the undoped GaAs.
Fig. 8. Temporal Q-switched pulse oscilloscope profile at the incident pump power of 6.7W. (a) The pulse profile of Q-switched laser with undoped GaAs. (b) The pulse profile of Q-switched laser with the Bi-doped GaAs.

Fig. 9. Temporal Q-switched pulse train oscilloscope profile (a). The profile of Q-switched laser with undoped GaAs. (b). The profile of Q-switched laser with Bi-doped GaAs.

4. Conclusions

In conclusion, diode-pumped passively Q-switched 2μm Tm:LuAG laser by using undoped GaAs or Bi-doped GaAs saturable absorbers is demonstrated for the first time. Compared to the performance of Q-switched laser with undoped GaAs saturable absorber, the laser with Bi-doped GaAs can produce shorter pulses and higher peak power at almost the same incident pump power. For Bi-doped GaAs saturable absorber, a maximum average output power of 0.73W is obtained under an incident pump power of 6.7W. The shortest pulse duration of 63.3ns under a repetition rate of 132.7 kHz is generated. And the highest single pulse energy and maximum peak power are measured to be 5.51μJ and 87.5W, respectively. The experimental results indicated that Bi-doped GaAs can be an attractive candidate of saturable absorber for 2μm laser.

Acknowledgments

This work is partially supported by the National Science Foundation of China (21173134, 21473103), the Natural Science Foundation of Shandong Province (ZR2014FM035), and the open project of Infrared Imaging Materials and Devices Laboratory of Chinese Academy of Sciences (IIMDKFJJ-12-07, IIMDKFJJ-14-07).