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Simultaneous Q Switching and Mode Locking with Narrow Envelope Width in a Microchip Nd:YVO$_4$ Laser with a Composite Semiconductor Absorber

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Abstract—By using a composite semiconductor absorber and an output coupler, we demonstrated a Q-switched and mode-locked diode-pumped microchip Nd:YVO$_4$ laser. With a 350-μm-thick crystal, the width of the Q-switched envelope was as short as 12 ns; the repetition rate of the mode-locked pulses inside the Q-switched pulse was more than 10 GHz. The average output power was 335 mW at a maximum pump power of 1.6 W. Q-switched envelope widths of 21 and 31 ns were also achieved with crystals 0.7 and 1.0 mm thick, respectively.

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The compact and simple microchip laser can provide picosecond-short pulses in Q-switching operation [1–3] and pulses with a 10-GHz repetition rate in mode-locked operation [4–6], which makes it interesting for a variety of scientific and industrial applications such as medicine, lidar, communication, and optical clocks [2, 7, 8]. Simultaneous Q switching and mode locking as a special experimental phenomenon has been studied in recent years for the higher peak power relative to cw mode-locked pulses for similar current injection; different saturable absorbers were used in these experiments, such as Cr^{4+}:YAG crystals, GaAs wafers, and LiF:F$_2$ [9–11]. Recently, the LT In$_{0.25}$Ga$_{0.75}$As was realized to be a better saturable absorber for solid state lasers because of its excellent nonlinear absorption, simple growth technology, and compact design for the laser cavity [12]. Using the absorber, the mode locking of several laser crystals such as Nd:YVO$_4$, Nd:GdVO$_4$, and Nd:GdYVO$_4$ has been demonstrated [13–15]. Using the SESAM and microchip laser, cw mode-locked pulses with a 160-GHz repetition rate have been obtained [6], but using the SESAMOC only Q-switching pulses were achieved [16]. In this article, using a composite semiconductor absorber and an output coupler, we achieved Q switching and mode locking operation of the microchip laser. The width of the Q-switched envelope was about 12 ns; the repetition rate of the mode-locked pulses inside the Q-switched pulse was more than 10 GHz. As far as we know, this is the first demonstration of a composite semiconductor absorber for Q switching and mode locking of the microchip laser.

Figure 1 shows the experimental configuration for the passively Q-switched and mode-locked microchip Nd:YVO$_4$ laser with the composite semiconductor absorber. The pump source was an 808-nm diode laser with a strip size of 200 μm. We controlled the diode working temperature with a thermo-electric coolers so that we could adapt the pump wavelength to the maximum absorption by the laser crystal. Through a coupler system, a 90-μm pump spot was focused into the laser crystal. The laser crystal was a 3.0 at % a-cut Nd:YVO$_4$ crystal with a thickness of 350 μm. One side of the crystal was coated with antireflection ($T > 98\%$) for the 808-nm pump wavelength and high reflection ($R >$

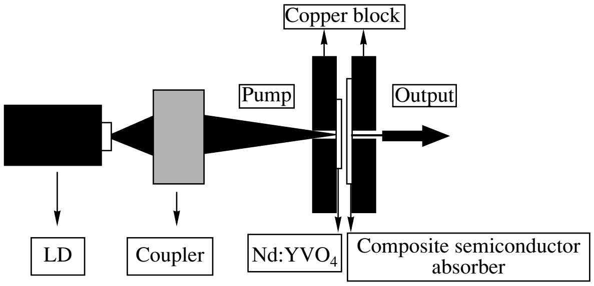

Fig. 1. Schematic of the Q-switched and mode-locked microchip Nd:YVO$_4$ laser.

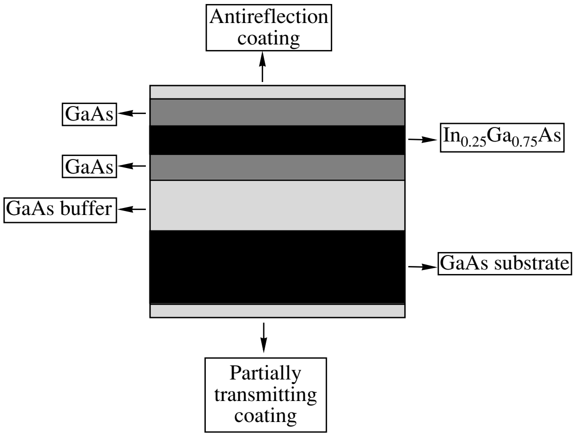

Fig. 2. The structure of the composite semiconductor absorber.

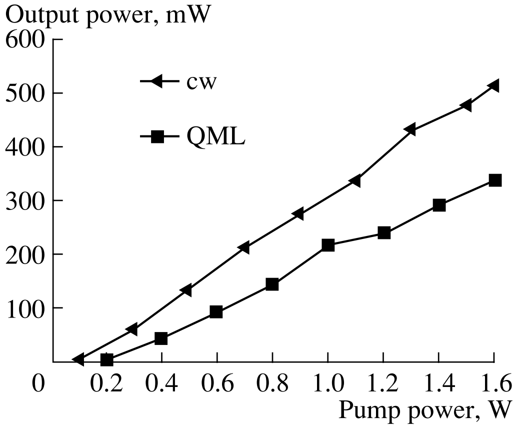

Fig. 3. Dependence of the output power on the pump power in cw and Q-switching and mode-locking (QML) operation.

99.8%) for the 1064-nm laser radiation; the other side was coated with antireflection ($T > 99.8\%$) at 1064 nm. To alleviate the thermal load, the crystal was attached to a copper block and cooled by thermo-electric coolers. The transmission of the absorber was about 6% at 1064 nm. The absorber was also attached to a copper block but was not temperature-controlled. The flat–flat cavity was composed by one side of the Nd: YVO_4 and one side of the absorber.

We used a composite semiconductor absorber in our experiment. The composite semiconductor absorber was made on the basis of pure (semi-insulating) GaAs substrate. First, a 500-nm GaAs buffer layer was deposited on the semi-insulating GaAs substrate by a MOCVD device. Second, about 15 nm of $In_{0.25}Ga_{0.75}As$ was grown upon the buffer layer at temperatures as low as 550°C. Finally, both sides of the GaAs substrate were polished and coated with an antireflectivity layer of less than 1% at 1064 nm. The large thickness of the $In_{0.25}Ga_{0.75}As$ would cause degradations such as surface striations, which would lead to too much nonsaturable losses, so we chose the GaAs/$In_{0.25}Ga_{0.75}As$/GaAs quantum well structure rather than bulk $In_{0.25}Ga_{0.75}As$.The quantum well was directly grown on GaAs buffer instead of a Bragg mirror composed of multiple pairs of GaAs/AlAs layers, leading to a broader bandwidth, a low cost, and a simple growth technology. In order to make the whole wafer as an output coupler, the two sides of the wafer were coated with dielectric films; one side was coated as antireflection and the other side as partial transmission at the laser wavelength; the total transmission of the device at 1064 nm was about 6%. The structure of the absorber is shown in Fig. 2. The composite semiconductor absorber is composed of two absorbers. One is the semi-insulating GaAs substrate itself; the other is the deposition layer (LT $In_{0.25}Ga_{0.75}As$), similar to a semiconductor saturable absorption mirror (SESAM), for mode locking.

The cw performance of the microchip laser at 1064 nm was studied first. The saturable absorber was replaced with an output coupler with 6% transmission at 1064 nm. In the cw operation, the laser threshold was about 100 mW and the output power was 510 mW at a maximum pump power of 1.6 W. The optic-to-optic conversion efficiency was about 32%. In Fig. 3, the laser output power is plotted as a function of incident pump power. The optimum cw performance provided the baseline for evaluating the passive Q-switching and mode-locking efficiency.

In the second part of the experiment, the Q-switching and mode-locking performance was studied by using the saturable absorber as the output coupler. The laser began to operate when the pump power exceeded 200 mW; the maximum output power was 335 mW at a pump power of 1.6 W. The low threshold and high optic-to-optic conversion efficiency (21%) indicated the low insertion loss of the saturable absorber. The dependence of the average output power on the pump power is shown in Fig. 3. When the pump power was about 1.1 W, the laser exhibited typical Q-switching and mode-locking operation; however, the mode-locking depth was relatively low. At a pump power of 1.5 W, the laser exhibited nearly perfect Q-switching and mode-locking behavior. The pulse train was monitored by a fast response photodiode and a LeCroy oscilloscope (9361C). Because of the low bandwidth of the oscilloscope, the mode-locking trains with a more than 10-GHz repetition rate inside the Q-switched envelope were not accurately depicted. The pulse is shown in Fig. 4. The Q-switching envelope width was as short as 12 ns.

Finally, we used two other Nd:YVO_4 crystals for the experiment, the thickness of which were 0.7 mm (2.0 at %) and 1 mm (1.0 at %). The film coating of the

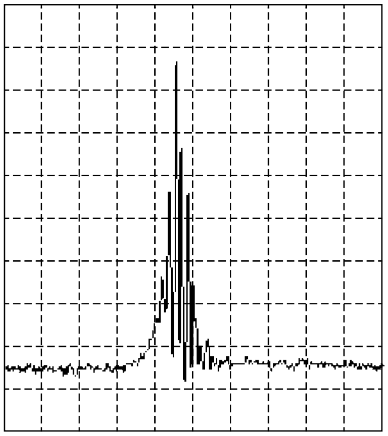

Fig. 4. The 12-ns-width Q-switched envelope pulse with 350-μm-thick Nd:YVO_4.

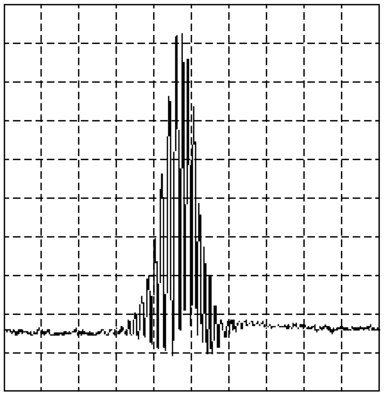

Fig. 5. The 21-ns-width Q-switched envelope pulse with 0.7-mm-thick Nd:YVO_4.

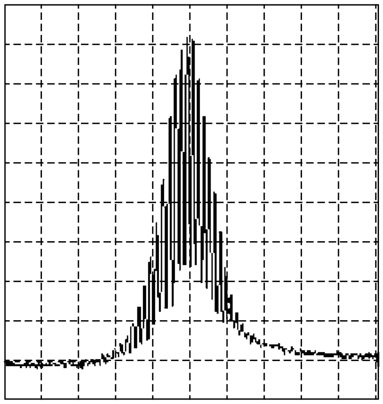

Fig. 6. The 31-ns-width Q-switched envelope pulse with 1-mm-thick Nd:YVO_4.

two crystals was the same as for the 350-μm-thick crystal, and the pump source was not changed. We also achieved Q-switched and mode-locked pulses of the two microchip lasers. As for the 0.7-mm-thick Nd:YVO_4, the Q-switched envelope width was about 21 ns, and the maximum output power was about 390 mW. For the 1-mm-thick Nd:YVO_4, the Q-switched envelope width was about 31 ns, and the maximum output power was about 470 mW. The Q-switched and mode-locked pulses of the two lasers are shown in Figs. 5 and 6 respectively.

Generally, we are able to obtain Q switching and mode locking whose Q-switched envelope is from several hundred ns to several microseconds in lasers with a Cr^{4+}:YAG absorber or GaAs. The short Q-switched envelope in our experiment may be attributed to the characteristics of the composite semiconductor absorber, which has a ps recovery time in an LT $In_{0.25}Ga_{0.75}As$ absorber and a ns recovery time in GaAs substrate. In this experiment, we obtained Q-switched mode locking, not cw mode locking. The criterion for the transition between the regimes of cw mode locking and Q-switched mode locking has been investigated [3]. Following the criterion, we can construe the phenomenon. The 6% transmission of the saturable absorber was high for the high-repetition-rate mode-locked laser; we think the transmission should be optimized to be about 1%. The modulation of the absorber related to the thickness of the absorber was also an important parameter for the microchip mode-locked laser; a small modulation would be a better choice. Finally, the stripe size of the diode laser was large and should be changed to a high bright one.

In conclusion, we have demonstrated a diode-pumped Q-switched and mode-locked Nd:YVO_4 microchip laser using a composite semiconductor absorber and an output coupler. A very short Q-switched envelope of about 12 ns was achieved, and a very high repetition rate mode-locked pulse of more than 10 GHz was enveloped in the short Q-switched laser pulse. At a maximum pump power of 1.6 W, the average output power reached 335 mW, which corresponded to a high optic-to-optic conversion efficiency of 21%.

REFERENCES

1. S. V. Voitikov, A. A. Demidovich, L. E. Batay, et al., Opt. Commun. **251**, 154 (2005).
2. B. Braun, F. X. Kartner, M. Moser, et al., Opt. Lett. **22**, 381 (1997).
3. G. J. Spuhler, R. Paschotta, R. Braun, et al., J. Opt. Soc. Am. B **16**, 376 (1999).
4. S. Lecomte, M. Kalisch, L. Krainer, et al., IEEE J. Quantum Electron. **41**, 45 (2005).

5. L. Krainer, R. Paschotta, M. Moser, and U. Keller, Electron. Lett. **36**, 1846 (2000).
6. L. Krainer, R. Paschotta, S. Lecomte, et al., IEEE J. Quantum Electron. **38**, 1331 (2002).
7. R. Ramaswami and K. Sivarajian, *Optical Networks: A Practical Perspective* (Morgan Kaufman, San Mateo CA, 1998).
8. D. A. B. Miller, IEEE J. Sel. Top. Quantum Electron. **6**, 1312 (2000).
9. Y. F. Chen, S. W. Tsai, and S. C. Wang, Opt. Lett. **25**, 1442 (2000).
10. Y. F. Chen, K. F. Huang, S. W. Tsai, et al., Appl. Opt. **40**, 6038 (2001).
11. Y. F. Chen, S. W. Tsai, S. C. Wang, and J. Chen, Appl. Phys. B **73**, 115 (2001).
12. Y. G. Wang and X. Y. Ma, Chin. Phys. Lett. **20**, 1960 (2003).
13. Y. L. Jia, Z. Y. Wei, J. A. Zheng, et al., Chin. Phys. Lett. **21**, 2210 (2004).
14. B. Y. Zhang, G. Li, M. Chen, et al., Opt. Commun. **244**, 311 (2005).
15. Y. G. Wang, X. Y. Ma, Y. X. Fan, and H. T. Wang, Appl. Opt. **44**, 4384 (2005).
16. G. J. Spühler, S. Reffert, M. Haiml, et al., Appl. Phys. Lett. **78**, 2 (2001).