# Chapter 6 Diode pumped passive mode locking Nd:LuVO$_4$ laser by semiconductor absorber crystal: Cr:YAG

## 6-1 Motivation

The purpose of this chapter is to eliminate the number of pulses within the Q-switching envelope such as in Fig. 5-4. Low transmission of Cr:YAG provides a high threshold for generation QML and therefore we believe it's a quite nice tool to avoid above problem. To realize this fact, we will show our experimental and simulated results of adapting a semiconductor absorber Cr:YAG crystal for Q-switch mode-locking the Nd:LuVO$_4$ laser in this chapter.

## 6-2 Experimental setup

The setup is similar with that of Fig. 4-1 except for the KTP is replaced by two Cr:YAG crystals with T = 40% and 80% and a dichroic mirror of R = 60% for 1064 nm and HR for 532 nm as an output coupler. We choose a new laser crystal Nd:LuVO$_4$ which has a better stimulated absorption and emission cross section at 808 nm and 1064 nm mentioned in Chapter 1.

## 6-3 Experimental results

The output power versus the pumping is shown in Fig. 6-1. Black squares represent CW operation and red circles are the QML results with insertion of Cr:YAG. Comparing the thresholds of T = 80% on the left of Fig. 6-1 with T = 40% one, we found the lower threshold of 4 W for T = 80% than for T = 40% of threshold ~10 W.

Shown in Fig. 6-2 are the oscilloscope traces of pulse trains of QML. There are vivid differences below: irregular pulse train with large fluctuation is observed in 80% but rather stable with small fluctuation in 40% Cr:YAG. See more carefully by viewing the time scales shown in both graphics which are not the same. Larger Q-switch pulse spacing in 40% of ~ 0.1 ms is 100 times larger than that in 80% one.

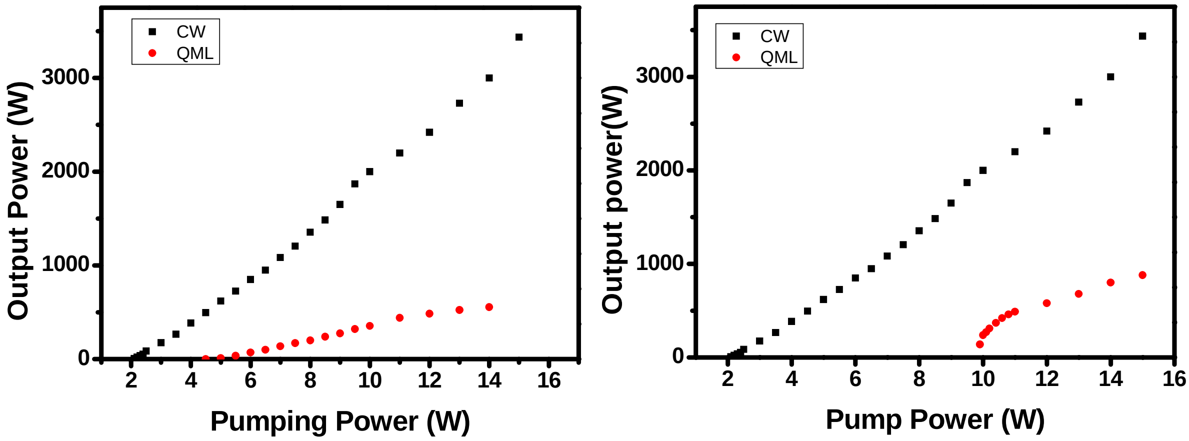

Fig. 6-1 Output versus pumping power of passive mode locking laser with 80% (Left) and 40% (Right) transmission Cr:YAG..

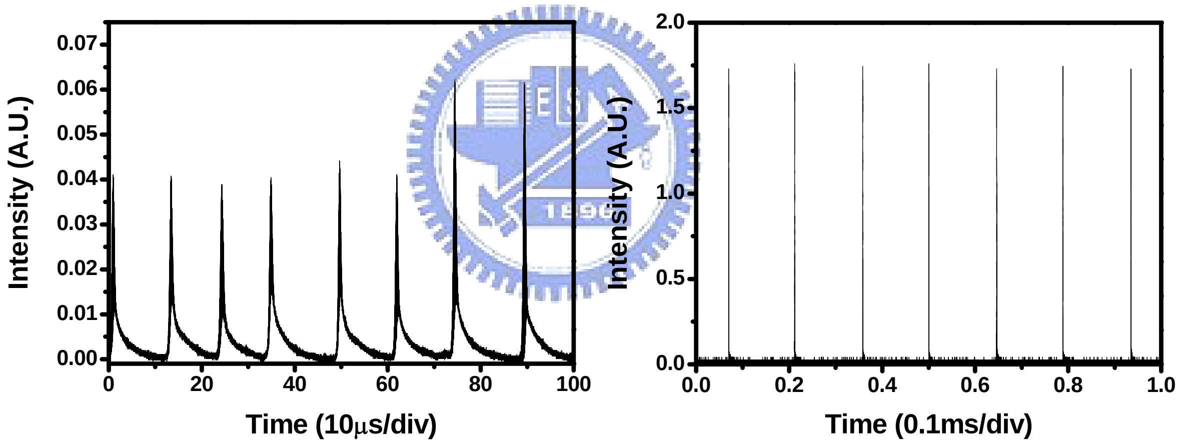

Fig. 6-2 Transmission = 80% (Left) and 40% (Right) Cr:YAG in QML state with irregular pulse train.

As we can see in the result of Fig. 6-3 (80%), the problem of too many mode locking pulses inside the Q-switch envelope (just like dual mode locking in Chapter 5) with FWHM of 0.38 μs, whereas, there are only about six mode locking pulses inside a Q-switch envelope (FWHM ~ 17ns) for T = 40% one in Fig. 6-4. It seems that we have succeeded in shortening the Q-switching pulse width.

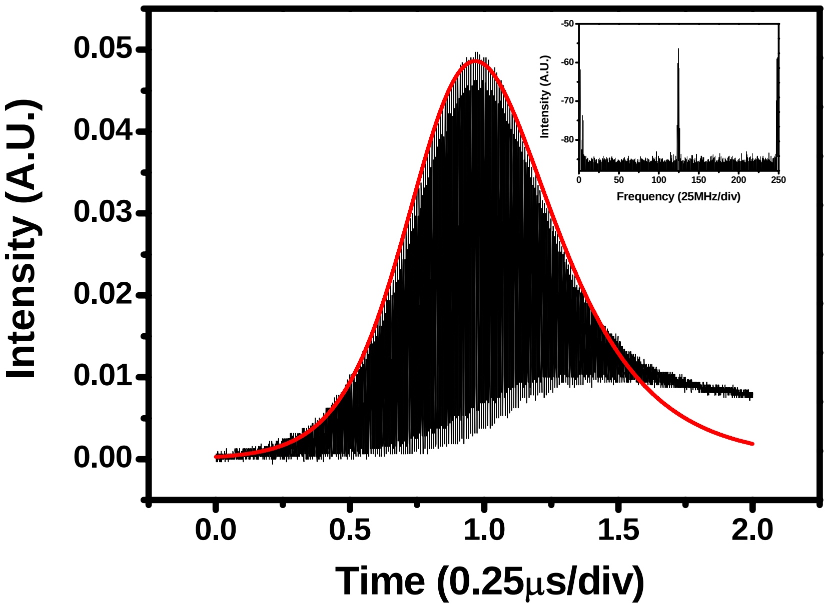

Fig. 6-3 Temporal expansion of Q-switching envelope of 80 % Cr:YAG with fitting curve in red line and RF spectrum inserted.

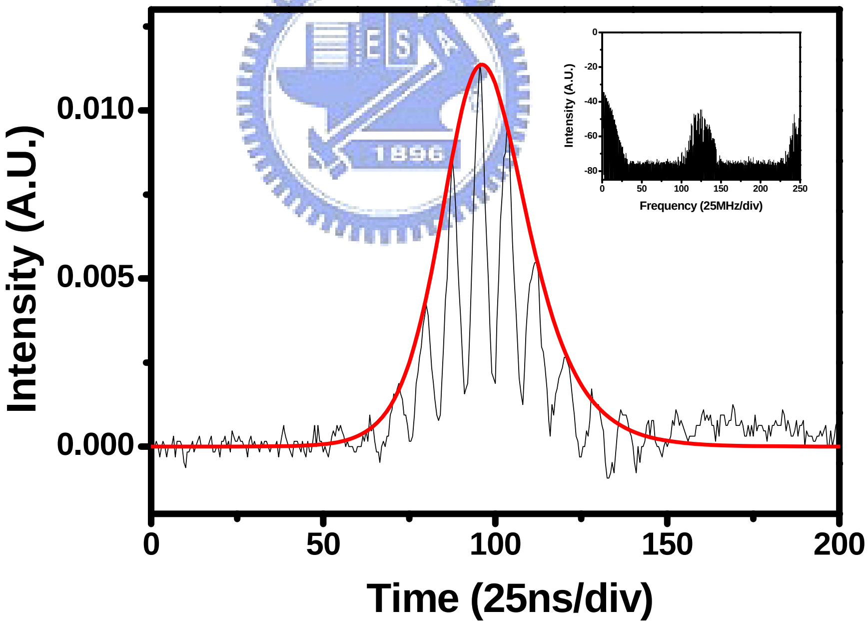

Fig. 6-4 Temporal expansion of Q-switching envelope of 40 % Cr:YAG with fitting curve in red line and RF spectrum inserted.

## 6-4 Simulation of Q-Switching mode-locking

In order to confirm our finding, we use the rate equations containing the cavity photon density in the gain medium and absorber population to simulate the temporal QML envelope. The output power of the laser can be expressed in terms of the photon density using Eq. (2-4.14). In Section 2-4, we have given the photon density recursion relation with all we knows factor in Eq. (2-4.12). By simulating Eq (2-4.12), we get the similar results seen on the oscilloscope as in Fig. 6-5, where Fig. 6-5(a) represents for 80% Cr:YAG and Fig. 6-5(b) is for 40% one.

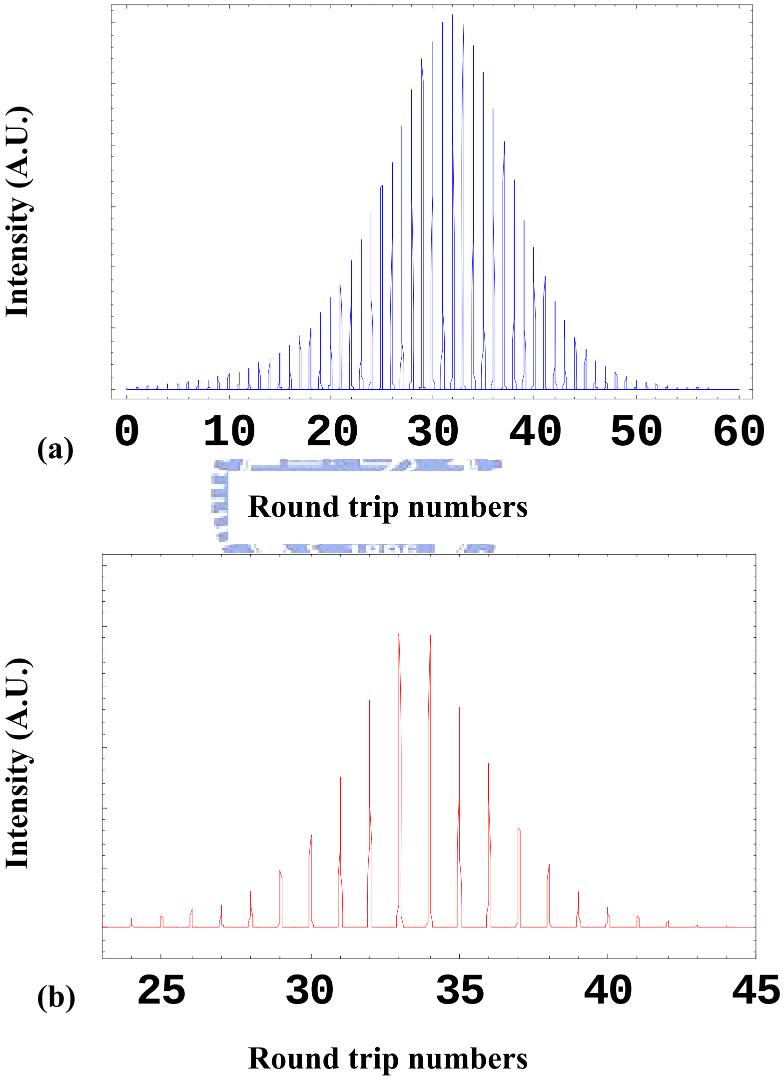

Fig. 6-5 Calculated results for the temporal shape of a single Q-switched pulse for saturable absorbers of T = 80% and T = 40% with R = 60%.

The tendency in Fig. 6-5 is consistent with our experiment show in Section 6-2. The key point is that 40% has fewer mode locking pulses in Q-switch envelope than 80% one. By using the simulation, we can predict the result of various kinds of reflections versus transmission of Cr:YAG before starting the experiment to prevent in-vain hard working. Varying the reflection of the output coupler R only changes the laser output power and threshold [1-2]. However, too high reflection will not provide enough modulation depth for mode locking pulse [1][3] and therefore it's just like the mode-locked pulses added on a AC values shown in Fig. 6-3 which it wipes out the bottom part of the Q-switching envelope.

In the following simulations we only alter the transmission of Cr:YAG and fix the output coupler at R = 60%. The time expansion of one QML envelope for T varying from 50% to 70% is shown in Fig. 6-6.

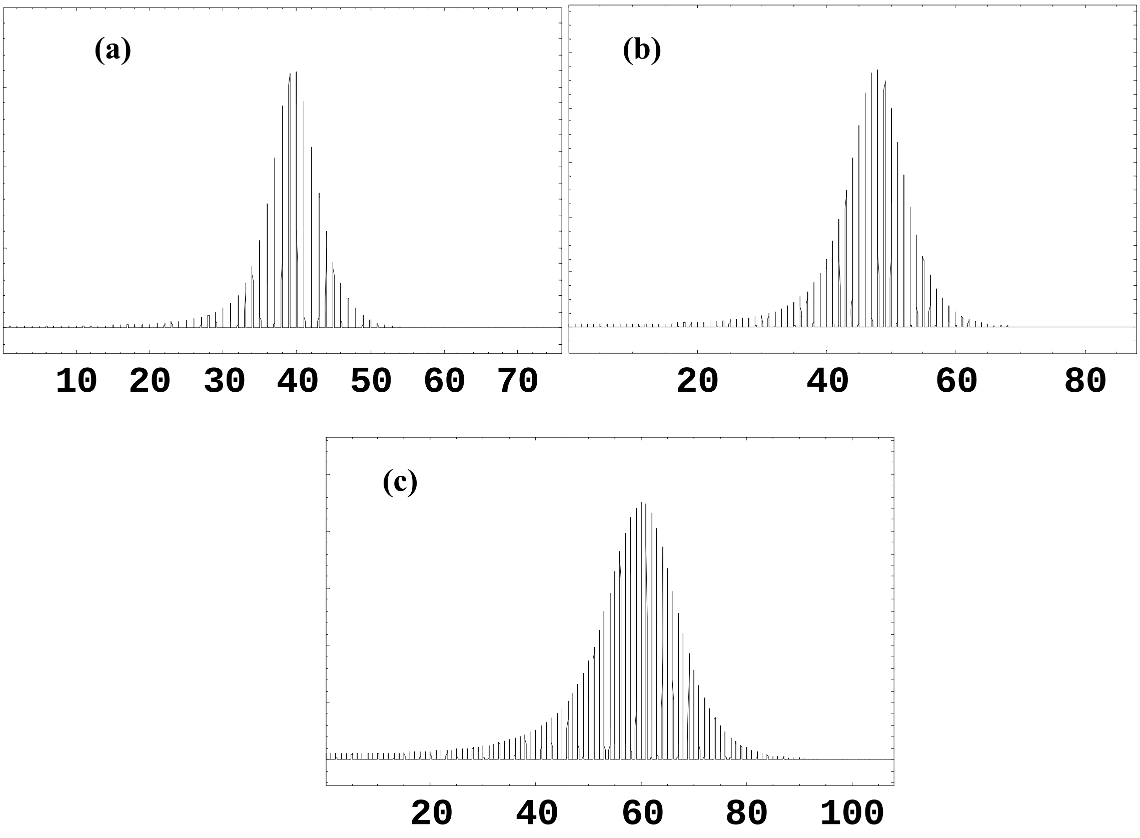

Fig. 6-6 Calculated results for the temporal shape of a single Q-switched pulse for saturable absorbers of (a) T = 50%, (b) T = 60%, and (c) T = 70% with R = 60%.

As expected in Fig. 6-6 (a)-(c) more pulses is produced inside the envelope with the higher transmission of Cr:YAG. The strong evidence of Fig. 6-6 also convinces us that the lower transmission could perform a better result for generating the QML, however, the higher threshold has to pay for penalty.

## 6-5 Discussion

Our central idea is to produce a high peak power and low repetition pulse laser, from the results of previous section, the Cr:YAG of T = 80% is operated with unstable QML state, We therefore only concentrate on the case of 40% Cr:YAG. It can be easily found that repetition rate increases gradually with adding the pumping power, thus, the peak power can be easily evaluated using the formula below:

$$\mathbf{P_p = \frac{P_{av}}{Rn\tau_p}}, \qquad (6\text{-}1)$$

where $P_p$ is the peak power, $P_{av}$ is the average power, R is the repetition rate, n is number of modes in a Q-switching envelope, $\tau_p$ is the pulse width of mode locking pulses. From the average output power shown in Fig. 6-1 and repetition rate from Fig. 6-2, we plotted the peak power and the repetition rate as a function of the absorbed pumping power in Fig. 6-7.

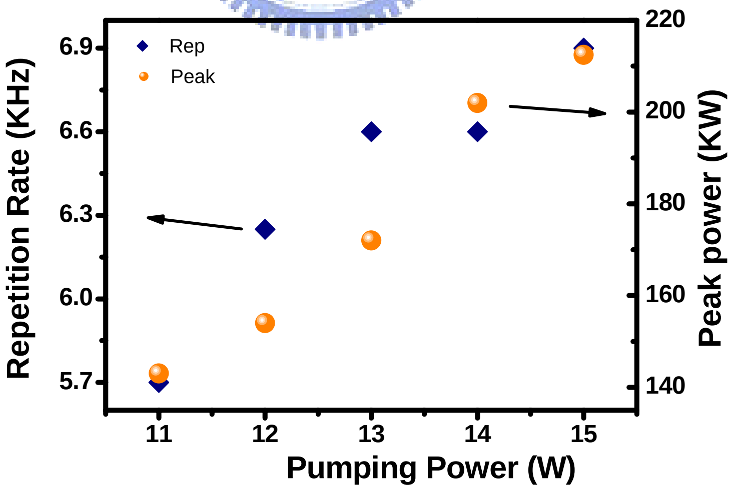

Fig. 6-7 Average output power and pulse repetition rate of the Q-switched pulse train on the absorbed pump power.

The shortest pulse width is 48 ps we can get at 11W pumping power. After all, we find that the pulse-widths are oscillating around 100 ps with increasing the pumping power. So as to prevent exaggerating the peak power and make the estimating method easier, we assume the pulse-width all equal to 100 ps.

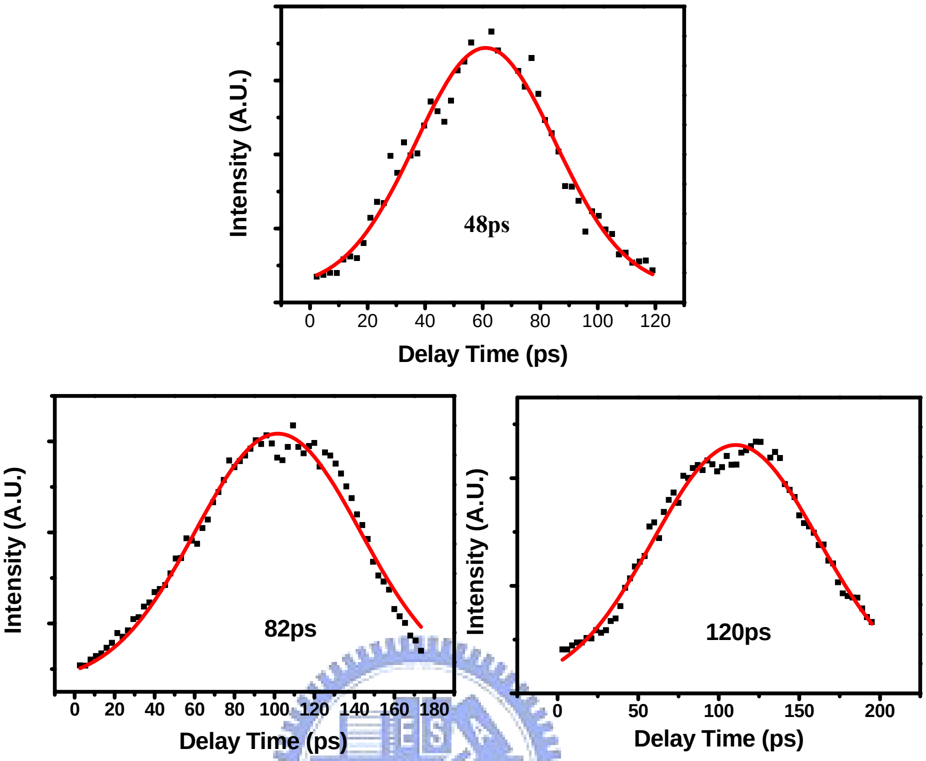

Fig. 6-8 Auto-correlation pulses ranging from 48 ~120 ps.

Back to Fig. 6-7, we observed the peak power of our system reaching the order of hundreds of kW. Keys to such a success have two essential points: one is the reducing repetition rate of Q-switch to ~ 6 kHz, estimated from Fig. 6-2; the other is the reducing number of mode locking pulses in the Q-switching envelope as Fig. 6-3. Contrarily, the repetition rate for 80% one is 50 ~ 100 kHz, which is 10 times or even higher than the 40% one. Comparing with other cavity dump of 30 kHz [4-5] and multi-pass cavities of 4 MHz or lower [6-10], our T = 40% case is also amazing in many aspect such as low cost and easy to construct. Lower repetition with higher pulse energy also presents in Fig. 6-9 with the formula,

$$Ep=P_{av}/R. \qquad (6\text{-}2)$$

We clearly declare in Figs. 6-3 and 6-4 that the number of pulses under the Q-switch envelope of T = 40% one is rather less than the 80% dense one's that agrees with the other's QML [11-12]. It thanks for choosing low transmission of 40% Cr:YAG absorber.to eliminate Q-switching pulse width. As a result, giant pulse energy with sub-mJ was first time to our knowledge demonstrated with Cr:YAG saturable absorber in Nd:LuVO$_4$ laser. Our Q-switching mode-locking Nd:LuVO$_4$ laser has achieved a repetition rate of 6 kHz and mode-locking pulse-width 100 ps with huge peak power of 200 kW and pulse energy of 0.1 mJ. Thus, efficient white light supercontinuum generation will become possible for use in material characterization.

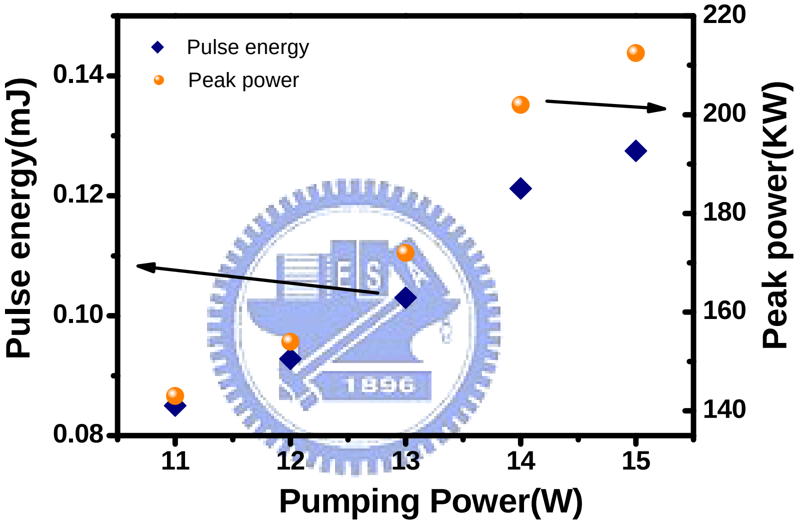

Fig. 6-9 Pulse energy and peak power of the Q-switched pulse train on the pump power.

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