Chapter 5　Regular Q-switching mode locking: Combination of nonlinear mirror and semiconductor saturable absorber mirror

5-1 Motivation

Since we demand high peak power and low repetition rate output in Nd:GdVO$_4$ laser using nonlinear mirror absorber and SESAM, in this chapter, the experiment setup is slightly different from the previous ones in Chapters 3 and 4.　In order to prevent damage of SESAM at high intra-cavity peak power, SESAM (the same as Chapter 2) is inserted at the position where has a larger radius of ~ 400 μm, estimated in use of the ABCD law. The idea of dual mode locking is that the SESAM plays the role of Q-switching due to large spot size and nonlinear mirror plays the role of mode-locking.　Therefore, the dynamics of the pulses and the ranges of the ML state as the position of KTP insertion were investigated in our dual mode locking laser.

5-2 Experimental setup

We combine NLM and SESAM in our cavity to present stable Q-switch mode locking. The experimental setup in Fig. 5-1 is a modified version of the setup of Fig. 4.1.　We folded the length l_2 into two parts l_2 and l_3 by a SESAM and the nonlinear mirror is consisting of a curved mirror M$_2$ (R = 500 mm), a KTP (10 mm), and an output coupler (OC with R = 80% for 1064nm and HR for 532nm).
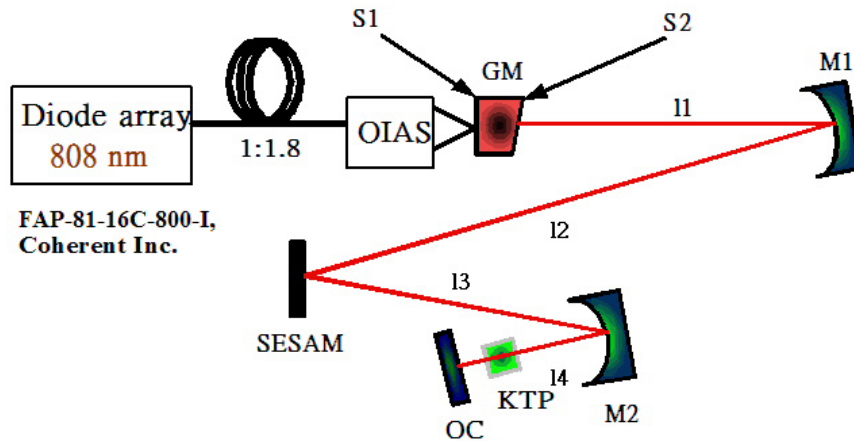
Fig. 5-1 Passively mode-locked structure with dual mechanisms: combing the NLM and SESAM.

5-3 Experimental results

The output power versus the pump power as the position of KTP insertion is shown in Fig. 5-2. The threshold pump power P_p for CW lasing (black squares) is 2 W and the slope efficiency is 10%. Unlike the previous mode locked $Nd:GdVO_4$ laser in use of only NLM, it transfers to CW-ML state at the relative low pump power of P_p=2.3 W. The ranges of QML state between CW and CW-ML state are relative short by using only NLM in $Nd:GdVO_4$.

In Fig. 5-2, the laser turns into irregular QML state at P_p=2.9 W (red triangles in Fig. 5-2) whose Q-switching envelopes seriously vary with time. At P_p =11.3 W, the QML pulse trains (blue stars) becomes stable and regular as in Fig. 5-2. The highest output power of 2.1 W can be generated for regular QML state at the pump power of 15 W.

Irregular QML pulse trains with large amplitude variation and timing jitter will be produced by the SESAM only if the KTP is absent in the cavity at pump power of 12 W as shown in the left hand side of Fig. 5-3. Thus, we can confirm that the influence of the SESAM is really existed. While the KTP is placed at the proper position near the OC, regular QML pulse trains having periodic amplitude variation and equally time spacing are

displayed in the right hand side of Fig. 5-3. The modulation frequency of Q-switching envelope is about 140 KHz that corresponds to 7 µs time period. Comparing two graphs of Fig.5-3, the experiment results are quite accordant with our motivation.
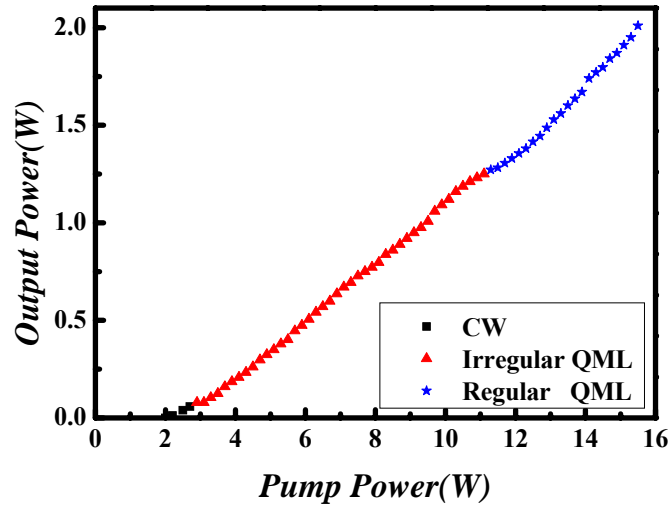

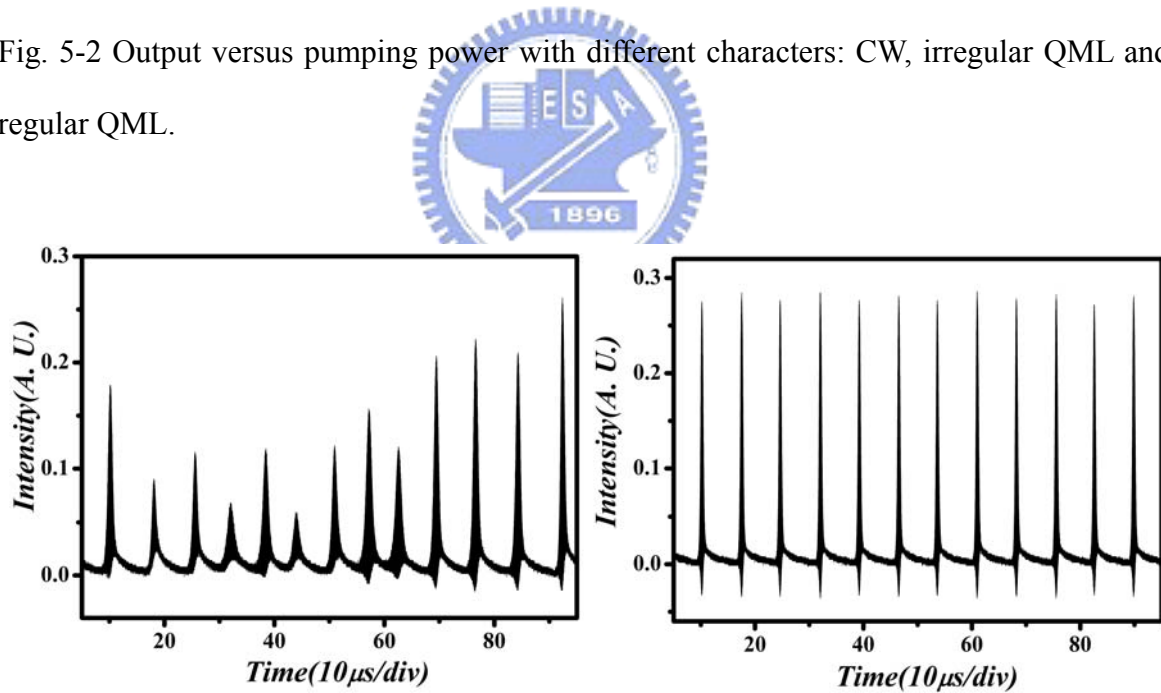Fig. 5-2 Output versus pumping power with different characters: CW, irregular QML and regular QML.

Fig. 5-3 Irregular (left) and regular (right with KTP inserted) QML pulse train.recorded on the oscilloscope

5-4 Discussion

The time expansion of the QML pulse trains are shown in Fig. 5-4, within which the CW- ML pulses are contained.   The time spacing between CW-ML pulses, i.e. cavity round trip time, is about 7.7 ns.   By fitting the QML envelope with the formula

$$I = \{\frac{I_0}{1.76[e^{(\frac{t}{\tau(1+a)})} + e^{(\frac{t}{\tau(1+a)})}]}\}^2 ,\qquad (5\text{-}3.1)$$

we obtained the FWHM of each QML envelope $\tau = 0.36$ μs and the asymmetric parameter $a = 0.062$.   Therefore, we can estimate the rising time t_i and falling time t_f of the temporal profile of QML envelope and the symmetric factor of the envelope γ, which is defined as

$$\gamma = \frac{t_i}{t_f} = \frac{1+a}{1-a} .$$

The closer to 1 of the symmetric factor, the more symmetry of the QML envelope is.   The value of γ in our QML envelope is 1.13 that shows good symmetry.   The pulse-width of QML pulses, measured by the homemade auto-correlator, is about 195 ps as showing in the inset of Fig. 5-4.
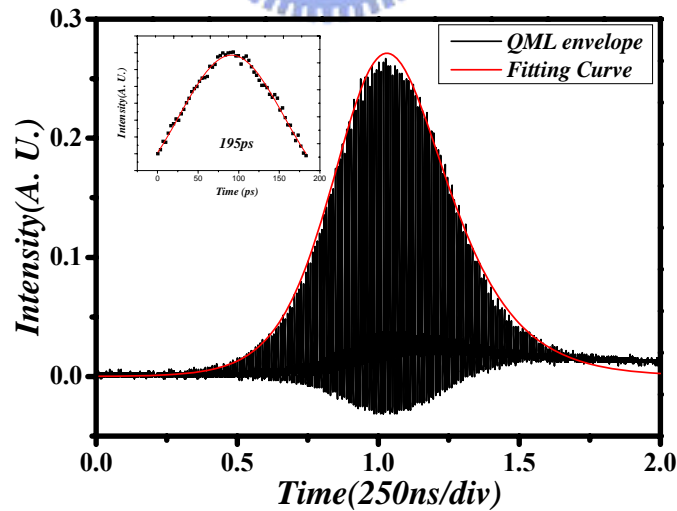

Fig. 5-4.   Time expansion of Q-switching envelope and red line is fitting result.

The variation of the measured pulse-width and the estimated peak power for QML pulses are shown in Fig. 5-5. The pulse-width shows slightly declining from 219 ps to 195 ps as the pump power increase from 12 W to 15 W. However, the repetition rate of QML envelope does not show apparently variation but fix at about 140 KHz. The peak power of QML pulses display linearly increasing from 1.03 to 1.73 kW and the largest energy output in each QML envelope is about 15 μJ. Here the estimation is considered the pulse-width ~ 200 ps, Q-switching modulation frequency of 140 kHz assuming about 46 pulses in each Q-switching envelope. Although multiple pass cavity can greatly reduce the cavity repetition rate [1] and increase the peak power of CW-ML pulses, it needs relatively high pump power for CW lasing which is above 10 W and near 20 W for CW-ML with relatively complicated cavity setup [2-3]. We have succeeded in use of a simple cavity setup for generating QML pulses to reduce the repetition rate of pulses and to enhance the peak power in use of the dual mode locking technique.
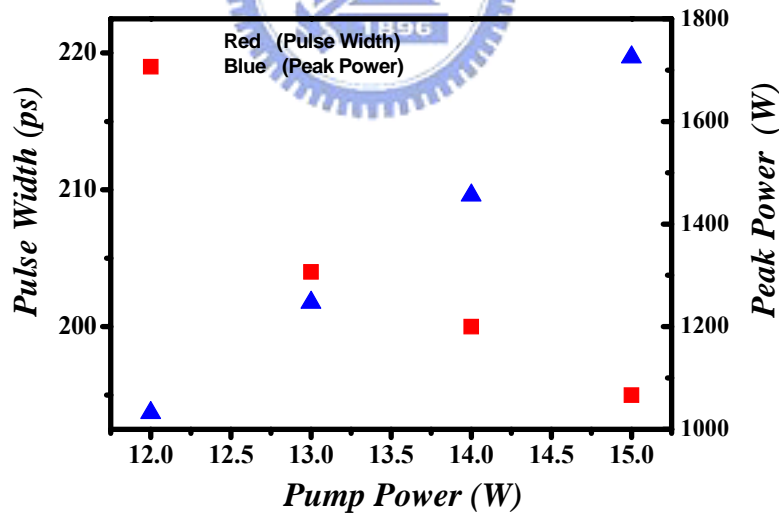

Fig. 5-5   Peak power versus Pulse width with different pumping power.

Finally, we briefly summarized in Table 5-1 comparing how the dual mode locking differs from the others. Due to the thermal fluctuation, both SESAM-CML and NLM-CML are easy to fluctuate at high pumping power, and thus it's not good for

generating regular mode-locking pulses.   In dual mode-locking, we can confine the system in the QML state.   Thus the lowest repetition rate of QML is 140 kHz about 1/1000 times lower than the CW-ML.   But the drawback is that it has a rather large pulse width 200 ps than 40, 20 or 15 ps in others [2-3].   The angle between SESAM, mirror M2, and OC is approximate 22°.   It causes astigmatism at KTP that maybe the reason causing such a wide mode locking pulse.   Summarizing all the conditions above, the peak power of dual ML seems the best one at ~ 1.73 kW.

Table 5-1   Comparison of different methods to generate passive mode locking used in this thesis.

Type	P_{pump}/P_{out} (W)	Repetition Rate (Hz)	Pulse Width (ps)	Peak Power (W)
SESAM (CML)	10/1	121M	15	550W(13nJ)
NLM (CML)	10/2.5	121M	40	516W(37nJ)
Dual (QML)	15/2.1	140K	200	1.725kW(15μJ)

If we are able to fix the large pulse-width problem, the ultra-large peak power could probably show in such a system.   The idea purposed by V. Couderc et al. [4-5] that compensate the dispersion by tuning the angle of KTP may be a wonderful technique for fixing the problem.   The other drawback in our result is there are too many mode-locking pulses within a Q-switch envelope or too wide the Q-switching pulse.   We will show shortening of Q-switch pulse in the next chapter.

References

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