國立交通大學

光電工程研究所

碩士論文

半導體雷射激發摻釹釩酸鎦雷射之聲光調變主動式Q開關鎖模雷射

Diode-pumped actively Q-switching and mode-locking Nd:$LuVO_4$ laser achieved by acousto-optic modulation

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中華民國九十八年七月

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半導體雷射激發摻鉫釩酸鎦雷射之聲光調變主動式Q開關鎖模雷射

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摘要

在腔內沒有額外鎖模元件的情況下，Q開關鎖模雷射已在由聲光調變器所調變的Q開關摻鉫釩酸鎦雷射中被觀察到。在我們的實驗中證實，如果要達到摻鉫釩酸鎦晶體的Q開關鎖模雷射，並不需要使聲光調變器的射頻頻率與雷射共振腔腔長倒數穩合，並且鎖模調變深度會隨著浦磊強度增強而增加。我們能得到最大至百分之一百的調變深度。這個現象可以用在雷射增益介質上所產生的光學克爾透鏡現象來解釋。同時，我們也得到了最佳的聲光調變頻率與雷射增益介質的螢光生命時間之間的關係。

除此之外，我們也藉由改變不同的共振腔長度，不同的腔內位置以及不同的聲光調變器的調變射頻和不同的浦磊強度，來更進一步的探討輸出功率與它們之間的關係。

Diode-pumped actively Q-switching and mode-locking Nd:LuVO$_4$ laser achieved by acousto-optic modulation

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Abstract

Q-switched mode locking (QML) has been observed in acousto-optic Q-switched Nd:LuVO$_4$ laser which is contained no mode-locking components. In our experiment proved that the match of acousto-optic modulator's radio frequency (AOM RF) and inverse cavity length is not a necessary criterion to achieve QML with c-cut Nd:LuVO$_4$ and the modulation depth was observed to increase with increased pumping power. The maximum modulation depth was as high as 100%. This phenomenon is explained by the introduction of optical Kerr-lens effect in the gain medium. A relation between optimal AOM RF and fluorescent lifetime of gain medium was also obtained in our experiments. Furthermore, we also discussed the output power by using different cavity length, different position inside the cavity, AOM RF, and pumping power to further investigate their relationship.

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在這大學和研究所的五年裡，學到了很多，途中也受過很多學長姐們的幫助，家宏學長，志賢，小豪，松哥，小郭，去年畢業的小新，阿詹，我的同屆好友阿肥，都幫助過我太多，尤其是指導我的陳厚仁學長以及許智章學長，更是在我的實驗與論文上，幫了我很大的忙，面對我各式各樣的問題，總是不厭其煩的指導我，常常和我一起討論到半夜，最後還要謝謝謝文蜂教授這五年來的指導和栽培，因爲您的循循善誘，才讓我總是在迷惘的時候找到方向，您不只是做實驗做科學的老師，更是在人生待人處事上的老師，謝謝您。

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2009.08.20

黃 棕儂

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Chapter 1 Introduction

1-1 Background

1-1.1 Laser modes of operation

The output of a laser may be classified into two categories by their modes of operation. A continuous constant output (known as continuous wave or CW) mode and a pulsed output mode by using the techniques of Q-switching, mode-locking, or gain-switching. In the CW mode of operation, the output of a laser is constant with respect to time. The population inversion required for lasing is continually maintained by a steady pumping source. In the pulsed mode of operation, the output of a laser varies with respect to time, typically taking the form of alternating 'on' and 'off' periods.

1-1.2 Pulse laser generation methods

The main methods of pulse laser generation are known as Q-switching, mode-locking, and pulsed pumping. In the following paragraph the basic concepts about mode-locking and Q-switching are presented.

A. Mode-locking

Mode-locking is a technique in optics by which a laser can be made to produce pulses of light of extremely short duration, on the order of picoseconds (10^{-12} sec) [1] or femtoseconds (10^{-15}sec) [2]. In a mode-locked laser, the mode-locked phenomenon is induced by a fixed phase relationship between the modes of the laser's resonant cavity. The laser is then said to be phase-locked or mode-locked. Interference between these modes causes the laser light to be produced as a train of pulses. These pulses are typically separated by the time that a pulse takes to complete one round trip in the resonator cavity.

B. Q-switching

Q-switching, sometimes known as giant pulse formation, is a technique by which a laser can be made to produce a pulsed output beam. The technique allows the laser resonator to generate sharp laser pulses with extremely high (MW) peak power, much higher than that would be produced by the same laser resonator which is operating in a CW mode[3-4]. In a Q-switched laser, the population inversion is allowed to build up by making the Q parameter unfavorable for lasing. After the pump energy has been stored in the laser medium, the Q parameter is adjusted to favorable condition, the sharp pulse is generated. It results in high peak powers as the average power of the laser is compressed into a shorter time frame.

Compared to mode-locked pulse laser, the Q-switching pulse laser leads to much lower pulse repetition rate, much higher pulse energies, and much longer pulse duration. And sometimes both the techniques are applied at once.

1-1.3 Application for Diode-pumped solid-state laser

As laser materials, the neodymium-doped vanadate crystals, such as Nd:YVO_4 [5-7], Nd:$GdVO_4$ [8-11] and Nd:$LuVO_4$ [12-17], have been proved to be the promising materials for diode-pumped solid-state lasers due to their good laser properties and high chemical stability. Diode-pumped solid-state lasers have been applied in many fields, including military, industry, medical treatment and scientific research, due to their excellent properties, including high efficiency, high reliability, compact structure and high beam quality.[18]

1-2 Motives

An acousto-optic (AO) effect, discovered in the twenties of last century, consisting in the diffraction of light beam on the "instantaneous", weak changes of refractive index induced in a transparent medium by the acoustic wave, has found numerous applications in several disciplines of optics and photonics. The optoelectronic devices exploiting this effect called later acousto-optic modulators (AOM) can be divided into two groups having in view their application in laser technology. In the first one, the AOMs are applied out of a laser cavity, and the second one is applied inside the resonator cavity.

Outside cavity types of AOM are as follows:

- AO amplitude filters and choppers
- AO Bragg frequency shifters
- AO angular scanners

Inside cavity types of AOM are as follows:

- AO-mode lockers
- AO-Q-switches
- AO tunable filters,
- AO-QML cells

However, even the AO mode locker widespread in seventies of the last century in several types of lasers, after invention of SESAMs, its role in modern laser technique has become to decrease. On the other hand, since AO-Q-switches invention at the beginning of the seventies, they have been the most widespread, especially in commercial medium and high power pulsed DPSSLs. The only competition for such type modulators are electro-optic (EO) cells. The properties of AO and EO Q-switches were compared in Table 1-1[19].

(τ_{rel} – lifetime of laser upper level)

Property	AO-q-switch	EO-q-switch
contrast	low (>1:10) ☹	high (<1:200) ☺
final losses	v. low <0.02 ☺	>0.05 ☹
switching time	>50 ns ☹	>2-5 ns ☺
max. PRF	> 100 kHz ☺	<100 kHz ☹
min. PRF	$>1/\tau_{rel}$ ☹	few Hz ☺
aberration / beam quality requirement	moderate ☺	high ☹
polarization requirement	yes or not ☺	high ☹
temperature stability requirement	low ☺	high ☹
supply	RF ☺	HV ☹
damage threshold	high > 1 GW/cm^2 ☺	< 1 GW/cm^2 ☹

Table 1-1 Comparison of properties and requirements for AO and EO

The main advantages of AOMs over EO-Q-switches are:

1. Much higher damage thresholds.
2. The simpler RF supply
3. The less stringent requirements on beam quality
4. Depolarization and reduce thermally induced aberrations
5. The higher level of pulse repetition frequency (PRF).

The main drawback is lower contrast (less than 1:10) and resulting problems with operation for low value of PRF [19].

1-2.1 The reason for choosing c-cut Nd:LuVO$_4$

As laser materials, the neodymium-doped vanadate crystals, such as Nd:YVO$_4$ [5-7], Nd:GdVO$_4$ [8-11] and Nd:LuVO$_4$ [12-17], were identified that the crystals cut along a and c axes have different properties.

The a-cut crystals have the advantages of large emission cross-sections and polarized laser output, and are suitable for the application in the CW laser experiments, but the c-cut crystals have the properties of the non-polarized laser output and small emission cross-section, and are suitable for the application in the pulsed laser experiments [18].

Nd:LuVO$_4$ is a new laser crystal and possess the same ZrSiO4 structure with Nd:YVO$_4$ and Nd:GdVO$_4$. Zhang's group have studied the growth and laser properties of Nd:LuVO$_4$ [21-23] and shown that Nd:LuVO$_4$ has high thermal conductivity (9.9 Wm^{-1}K^{-1}) [24] and appropriate fluorescence lifetime (95 μs) [22] for the 4F$_{3/2}$ level, and the a-cut crystal has the same excellent laser properties with that of Nd:YVO$_4$ and Nd:GdVO$_4$. But the laser properties at 1.06μm of c-cut Nd:LuVO$_4$ crystals have been largely ignored. However, the further study of c-cut Nd:LuVO$_4$ performance at the CW and pulsed LD-end-pumped laser at 1.06 μm done by Yu's group has demonstrated that the c-cut Nd:LuVO$_4$ is more suitable than a-cut one for the application in pulsed laser experiments[18]. The full width at half maximum of Nd:LuVO$_4$ crystal is about 8 nm at 808 nm, and the absorption coefficient is about 7.2 cm^{-1} at 808 nm (Fig. 1.1), so

Nd:LuVO4 crystal may be pumped by a laser diode (LD) at 808 nm.

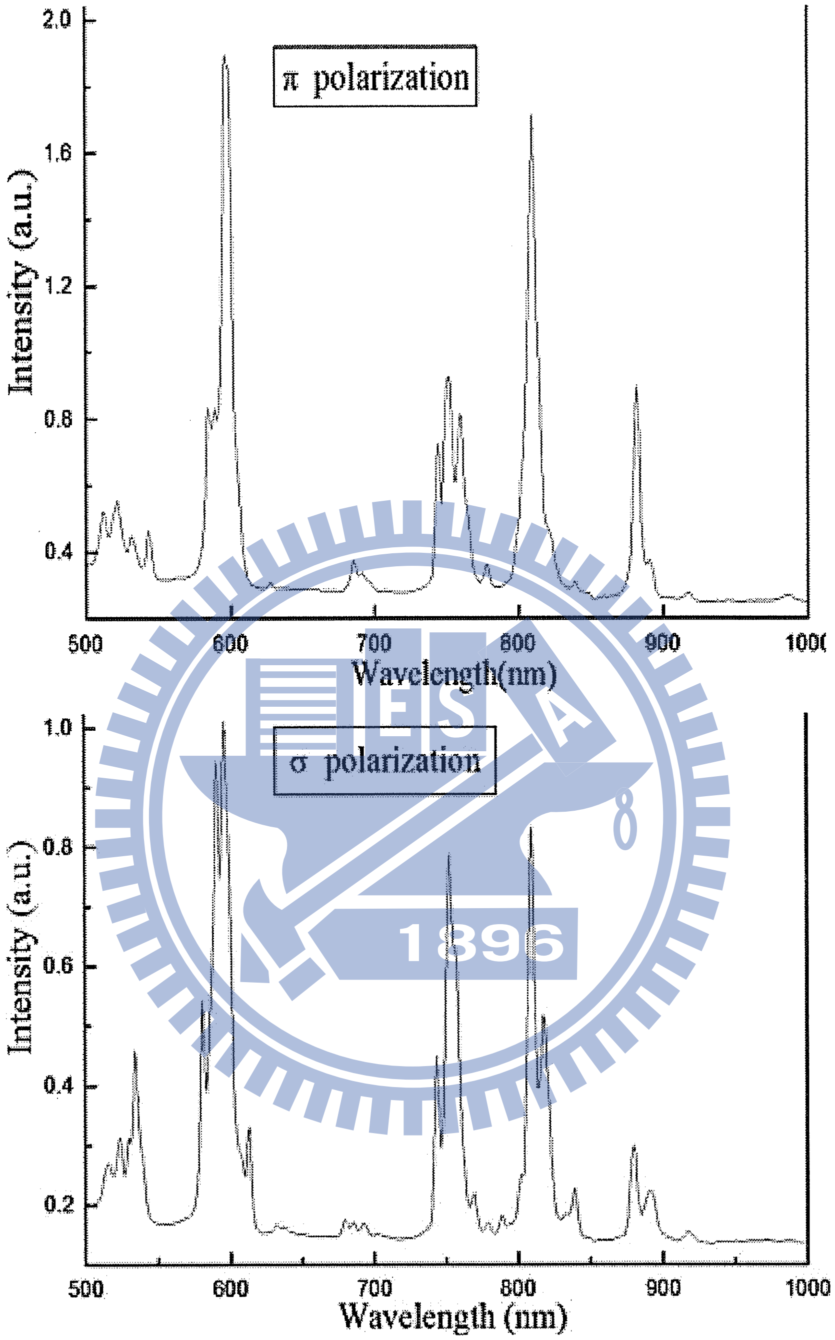

Fig. 1.1 Absorbance of doped Nd3+ ions in Nd:LuVO4.

From Fig. 1.2 shows the fluorescence spectrum of Nd:LuVO4 crystal measured from 960 to 1450 nm. There are two main emission peaks which central wavelength located in 1065 nm and 1343 nm and the former is the strongest peak of all the peaks. So we choose

1064nm as our resonant output.

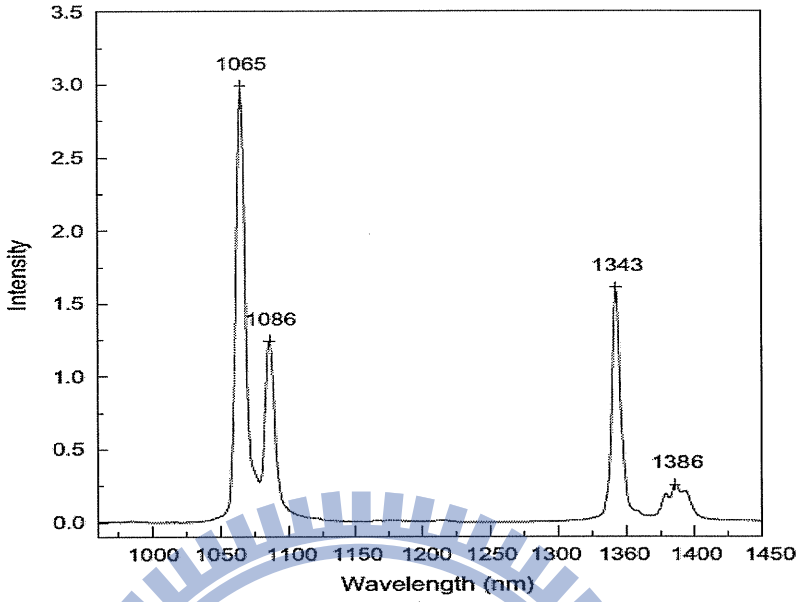

Fig. 1.2 Fluorescence spectrum of a Nd:LuVO_4 crystal.

Q-switched mode locking (QML) has been observed in acousto-optic Q-switched laser that contained no mode-locking components recently [19]. The principle of operation of acousto-optic-Q-switched and mode-locked (AO-QML) laser in Ref. [19] consists in enforcing the laser mode locked on the frequency equal to radio-frequency (RF) of AOM playing the double role of Q-switcher and mode locker. However, the reason which has been considered as an explanation of this effect was doubtable since the Q-switched mode-locking pulse could still be generated even with significant mismatch between the repetition rate of laser resonator with AOM RF [20]. However, not only the reason which causes the QML is questionable, the relationship between AOM optimal modulation frequency and maximum laser output has not fully discussed yet.

In order to further investigate the reason of QML in the laser resonator with only acousto-optic modulator and other puzzles mentioned above, we designed a serial of experiments to discuss the relationship between several independent variables which includes cavity length, AOM position inside the laser cavity, AOM modulation frequency, and pumping power. From the experiment result, we could come out explanations about the QML phenomena with AOM only.

1-3 Organization of the thesis

In this thesis, four chapters are given as follows. In Chapter 2, the basic theories of Q-switched laser, mode-locked laser and Q-switched mode-locked laser were discussed to generate optical pulses. In Chapter 3, the experiment setup will be given. In Chapter 4, we will show that the match of acousto-optic Radio frequency (AOM RF) to the cavity length is not a necessary criterion to achieve QML with c-cut Nd:LuVO$_4$. We also discussed the output power and QML effect by using different variables in the rest of Chapter 4. Finally, we summarize our results and discuss the future works in Chapter 5.

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Chapter 2

Mechanism of Q-switched and mode-locking

2-1 AO Q-switched laser

2-1.1 Principles of Q-switch

Q-switching is achieved by turning the quality factor or Q factor on and off (higher and lower) which is define as

$$Q = \frac{2\pi \times \text{Energy Stored}}{\text{Energy dissipated per cycle}} . \qquad \textbf{(2-1.1)}$$

A high Q factor corresponds to low resonator losses per round-trip, and vice versa. By putting some type of variable modulator inside the laser resonator, the Q-switch could be achieved. When the modulator is functioning, light which leaves the gain medium does not return, and lasing cannot begin, and when the modulator turned off, the light inside the optical cavity start to resonate and the lasing begins.

Initially the laser medium is pumped while the Q-switch is set to prevent feedback of light into the gain medium (producing an optical resonator with low Q). This produces a population inversion, but laser operation cannot yet occur since there is no feedback from the resonator. Since the rate of stimulated emission is dependent on the amount of light entering the medium, the amount of energy stored in the gain medium increases as the medium is pumped. Due to losses from spontaneous emission, after a certain time the stored energy will reach some maximum level; the medium is said to be gain saturated. At this point, the Q-switch device is quickly changed from low to high Q, allowing feedback and the process of optical amplification by stimulated emission to begin. Because of the large amount of energy already stored in the gain medium, the intensity of light in the laser resonator builds up very quickly; this also causes the energy stored in the medium to be depleted almost as quickly. The net result is a short pulse of light output from the laser, known as a giant pulse, which may have a very high peak intensity.

There are two main types of Q-switching, active Q-switching and passive Q-switching In our case, the Q-switch is a controlled through a variable AO modulator which may be replaced by some other forms of modulators such as an electro-optic device. The reduction of losses (increase of Q) is triggered by an AO modulator, and the pulse repetition rate (PRF) can therefore be externally controlled.

2-1.2 Principles of AO modulation

When an optical plane wave of wavevector **k** interacts with an acoustic plane wave of wavevector **q** to produce an optical plane wave of wavevector $\mathbf{k}_r = \mathbf{k} + \mathbf{q}$. Interaction between a beam of light and a beam of sound can be understood if the beam is regarded as a superposition of plane waves traveling in different directions, each with its own wavevector [1].

However, the scattering process could also be considered as one new photon and one phonon are generated while the incident photon is annihilated. In this case, the conservation law of energy yields

$$\omega_d + \Omega = \omega_i , \qquad \textbf{(2.1-1)}$$

where ω_d stands for the diffracted photon frequency, ω_i for the incident photon frequency, and Ω for the frequency of phonon.

Since the sound frequencies are below 10^{10} Hz and the optical beams are usually above 10^{13}Hz, we have $\omega_d = \omega_i + \Omega \approx \omega_i$, so $k_d \cong k_i$ and the magnitude of the two optical wavevectors is taken as k. According to Fig. 2.1-1, the magnitude of the sound wavevector is thus

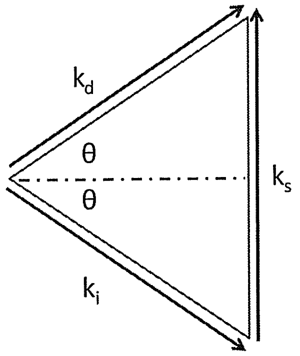

Fig. 2.1-1 The momentum conservation relation in Equation (2.1-1)

$$k_s = 2k\sin\theta\,. \tag{2.1-2}$$

Using K=2π/Λ, this equation becomes

$$2\Lambda\sin\theta = \lambda\,, \tag{2.1-3}$$

which is the same as the Bragg-diffraction condition with m=1.So when the light passing through the AO modulator, it will be deflected by an angle of θ, and we can use this mechanism to tune the Q-factor of laser cavity to achieve Q-switch pulse.

2-2 Kerr-lens mode-locking laser

2-2.1 Principles of mode-locking

Oscillation in an inhomogeneously broadened laser can take place at a number of frequencies, which are separated by (assuming a refractive index of n = 1)

$$\omega_q - \omega_{q+1} = \frac{\pi c}{1} \equiv \Omega\,, \tag{2-2.1}$$

where Ω is the free spectral range (or the mode spacing) in angular frequency and q is an integer. Now consider the total electric field on a reference plane resulting from such a multimode oscillation, say next to one of the mirrors, in the optical resonator. It can be taken, using complex notation [2], as

$$E(t)=\sum_m C_m e^{i[(\omega_0+m\Omega)t+\phi_m]}, \qquad \textbf{(2-2.2)}$$

where C_m and φ_m are the amplitude and the phase of the m-th mode. The summation runs over all the oscillating modes and ω_0 is chosen arbitrarily as oscillation frequency of one of the modes (usually chosen as the one closest to the line center). One property of Eq.(2-1-2) is that $|E(t)|$ is periodic in time with a period of $\tau \equiv 2\pi/\Omega = 2l/c$, which is the round-trip transit time inside the resonator. Using Eq. (2-1-2), the field at $t+\tau$ can be written

$$\begin{aligned}E(t+\tau)&=\sum_m C_m \exp\{i[(\omega_0+m\Omega)(t+\frac{2\pi}{\Omega})+\phi_m]\}\\ &=\sum_m C_m \exp\{i[(\omega_0+m\Omega)t+\phi_m]\}\exp(i\frac{2\pi\omega_0}{\Omega})+2m\pi)\\ &=E(t)\exp(\frac{i2\pi\omega_0 t}{\Omega}) .\end{aligned} \qquad \textbf{(2-2.3)}$$

Notice that $E(t+\tau)$ is identical to $E(t)$, except with a constant phase factor and the periodic property of $E(t)$ depends on the fact that the modes are equally spaced and the phases φ_m are fixed. In typical lasers the phases φ_m are likely to vary randomly with time. This causes the intensity of the laser output to fluctuate randomly and greatly reduces its usefulness for many applications where temporal coherence is important. It should be noted that this fluctuation takes place because of random interference between modes and not because of intensity fluctuations of individual modes.

Two ways in which the laser can be made coherent are: First, make it possible for the laser to oscillate at a single frequency only so that mode interference is eliminated. This can be achieved in a variety of ways, including shortening the resonator length l, thus increasing the mode spacing ($\Omega=\pi c/l$) to a point where only one mode has sufficient gain to oscillate. The second approach is to force the phases φ_m of all the modes to maintain their relative values (ideally zero, so that they all oscillate in phase). This is the so-called "mode locking" technique proposed and demonstrated in the early history of the laser. This mode locking causes the oscillation intensity to consist of a periodic pulse train with a period of $\tau \equiv 2\pi/\Omega = 2l/c$.

One of the most useful forms of mode locking results when the phases φ_m are made equal to zero. To simplify the analysis of this case, assume that there are N oscillating modes with equal amplitudes. Taking C $=1/\sqrt{N}$ m and $\varphi_m = 0$ in Eq. (2-1-2), we obtain

$$E(t+\tau)=\frac{1}{\sqrt{N}}\sum_{m=1}^{N}\exp i(\omega_0+m\Omega)t=\frac{1}{\sqrt{N}}e^{i[\omega_0+(N+1)\Omega/2]t}\frac{\sin(N\Omega t/2)}{\sin(\Omega t/2)}, \qquad \textbf{(2.2-4)}$$

where the field is normalized to a constant energy (independent of N). The last equality is obtained by summing up the geometric series. The average laser power output is proportional to E(t)E*(t) and is given by

$$P(t)\propto\frac{1}{N}\frac{\sin^2(N\Omega t/2)}{\sin^2(\Omega t/2)}, \qquad \textbf{(2-2.5)}$$

where the averaging is performed over a time that is long compared with the optical period $2\pi/\omega 0$ but short compared with the modulation period $2\pi/\Omega$.

Some of the analytic properties of P(t) are immediately apparent:

1. The power is emitted in a form of a train of pulses with a period τ=2l/c, i.e., the round-trip transit time.
2. The peak power, P(sτ) (for s = 0, 1, 2, 3, . . .), is equal to N times the average power, where N is the number of modes locked together.
3. The peak field amplitude is equal to N times the amplitude of a single mode.
4. The pulse width of the main peaks, defined as the time from the peak to the first zero is $\tau_0 = \tau/N$. This is approximately the FWHM of the main peaks of P(t) (for N >> 1).

There are (N-2) sidelobes between the neighboring main peaks.

The number of oscillating modes can be estimated by N $\cong \Delta\omega/\Omega$, that is, the ratio of the transition line width $\Delta\omega$ (or gain bandwidth) to the frequency spacing between the modes. Using this relation, as well as $\tau = 2\pi/\Omega$ in $\tau_0 = \tau/N$, we obtain

$$\tau_0 \approx \frac{2\pi}{\Delta\omega} = \frac{1}{\Delta\nu} = \frac{\tau}{N}, \tag{2-2.6}$$

where $\Delta\upsilon$ is the gain bandwidth. Thus the temporal length of the mode-locked laser pulses is approximately the inverse of the gain line-width.

2-2.2 Principles of Kerr-lens mode-locking

Kerr-lens mode- (KLM)locking achieves fast saturable absorber action by using intracavity nonlinear self-focusing effects which are produced by the nonlinear index of refractionn_2 of the solid state laser gain medium or a nonlinear medium such as KTP which is introduced in the cavity. The equivalent saturable-absorber action in KLM can be explicitly designed through a suitable choice of cavity parameters and the nonlinear intracavity material.

The cascaded second-order nonlinearity can cause large third-order susceptibilities from an intracavity second harmonic crystal. The nonlinear phase shift that originates in the nonlinear crystal is converted into a nonlinear amplitude modulation by a suitable intracavity aperture. This phenomenon can be briefly described as follows: when a beam propagates in a medium with a χ^2 nonlinearity out-of-phase-matching, the partially generated second harmonic is converted back into the fundamental frequency, in phase quadrature with respect to the original wave. There is therefore a phase shift in the fundamental frequency beam proportional to its intensity, as in a medium with a χ^3 nonlinearity (Kerr-medium), which can result in self-focusing action [3-7].

In Refs.[8–12], the Nd-doped crystals such as Nd:GdVO$_4$ were considered as Kerr-medium. So the c-cut Nd:LuVO$_4$ crystal should be regard as a Kerr-medium as well, which has a large nonlinear refraction index and can also induce self-focusing effect. That is to say, the influence of the gain medium c-cut Nd:LuVO$_4$ crystal to mode-locking in our experiments could be significant, and should be considerate.

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Chapter 3 Experimental setups

3-1 Schematics of diode-pumped Q-switched mode-locked $Nd:LuVO_4$ laser

The schematic setup of our laser with z-folded configuration is shown in Fig. 3-1.1.A fiber-coupled diode-array laser (FAP-81-16C-800-I, Coherent Inc.) with center wavelength of 808 nm was used as the pump source. The output beam from the fiber was imaged onto the laser crystal, which is a 3x3x8 mm^3 c-cut $Nd:LuVO_4$ crystal (with 0.5-at.% Nd^{3+} concentration), through an 1:1.8 optical imaging accessory (OIA's, Coherent Inc.). One side of laser crystal (S1) is high reflection (HR) coated at 1064 nm and anti-reflection (AR) coated at 808 nm as an end mirror of the resonator; while the other side (S2) is AR coated at 1064 nm. Two curved mirrors M1 and M2 with radii of curvatures of 500 and 200 mm were used as folding mirrors to conduct cavity beam through an AO modulator to the output coupler (OC). The distance between the gain medium and M1 is 30 cm that from M1 to M2 is 80 cm and from M2 to OC is 11.5 cm. We put a AO modulator (Neos 33041-10-1-I) with a 40.68MHz radio modulation frequency in the cavity at positions of 10 cm from gain medium (labeled as front), 40 cm from gain medium (middle), and at the output coupler (rear), respectively.

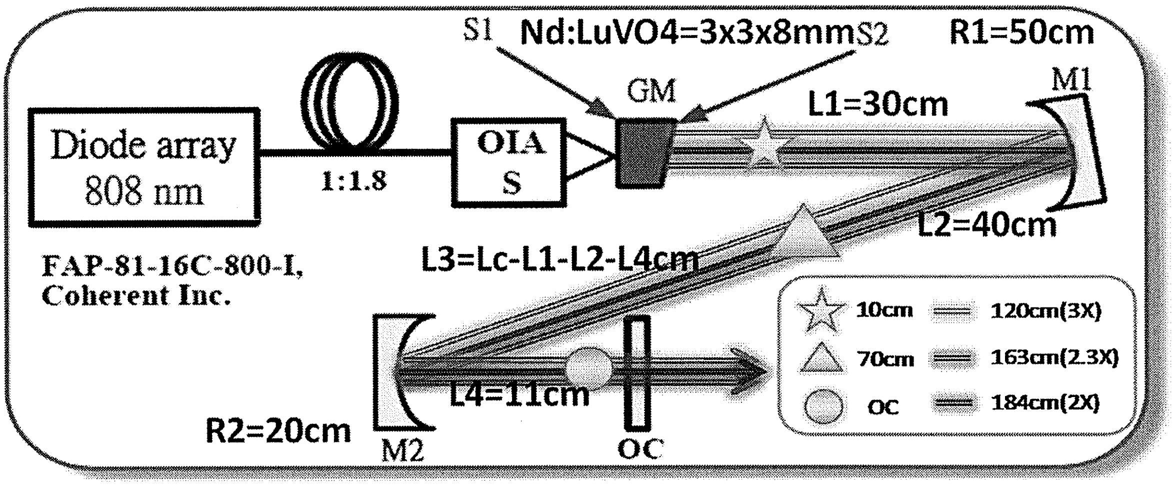

Fig. 3-1.1 Experiment setup

The output of the Nd:LuVO$_4$ laser from either OC or the wedged facet of the laser crystal was measured by a power meter (Ophir Inc.) or detected by a high speed InGaAs detector (Electro-Physics Technology, ET 3000) that was connected to an oscilloscope (LeCroy LT372, bandwidth 500 MHz).

In this experiment, we designed five different cavity lengths, which are 99, 120, 150, 164, 183cm, and monitored the output with different AOM MF, pumping power, and AOM location inside the cavity.

Chapter 4 Results and Discussion

4-1 QML in non-integer-cavity length of AOM RF

We have successfully demonstrated a QML pulse laser with more than 85% modulation depth in the non-integer-cavity length with an AO modulator (Fig. 4.1~3).

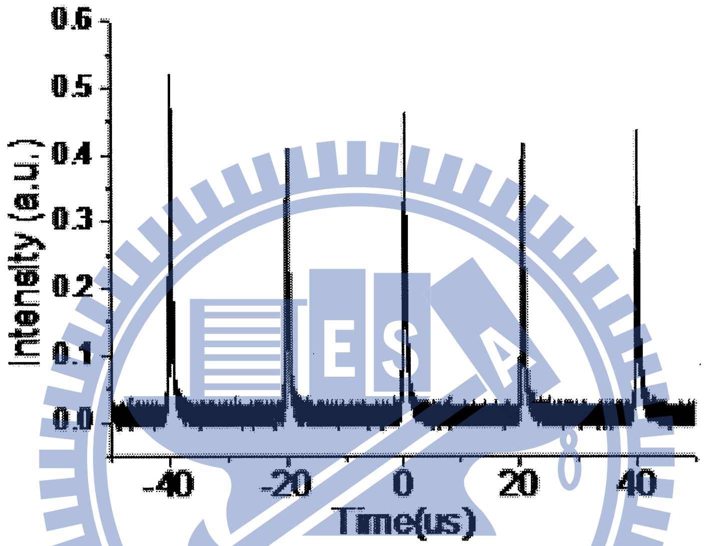

Fig. 4.1 QML with 163cm cavity length at 50 kHz of AO MOF and15W pumping power (20μs/div)

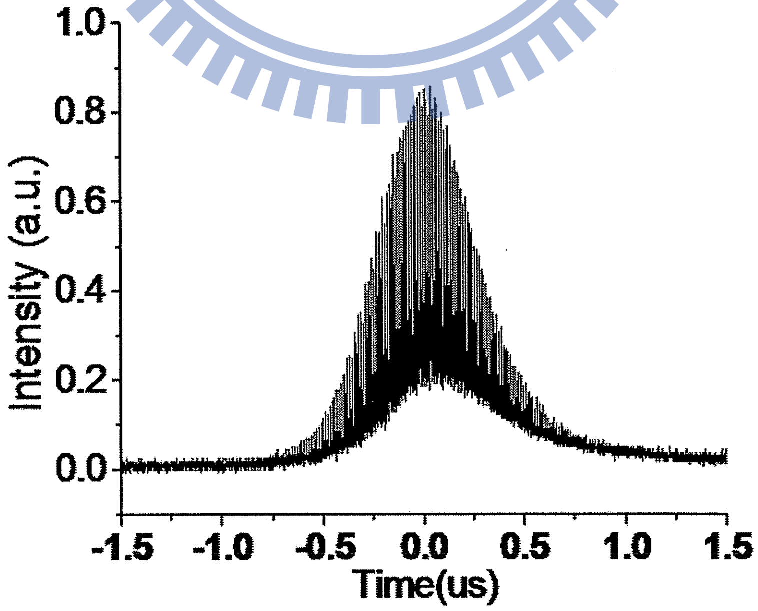

Fig. 4.2 QML with 163cm cavity length at 50 kHz of AO MOF and15W pumping power(1μs/div)

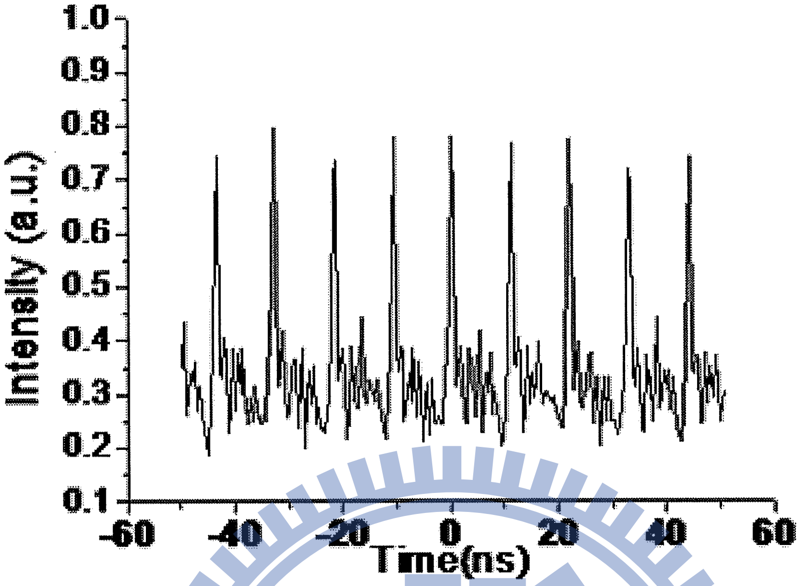

Fig. 4.3 QML with 163cm cavity length at 50 kHz of AO MOF and15W pumping power (20ns/div)

The QML were believed caused by enforcing the laser resonator mode locking on the frequency equal to radio-frequency (RF) of AOM, which plays the double roles of Q-switcher and mode locker. However, we will demonstrate here that the match between mode locking frequency and AOM RF is not a necessary criteria in c-cut Nd:LuVO$_4$. Since the Nd-doped crystal such as Nd:GdVO$_4$, Nd:YVO$_4$are regard as Kerr medium due to their high optical nonlinearity or large n$_2$. We believe that the QML effect in our experiment could be explained by Kerr-lens mode-locking effect.

To realize the above mentioned assumption, we applied the ABCD law to calculate the spot size at gain medium. To have stable cavity it requires that,

$$q_s = \frac{Aq_s + B}{Cq_s + D}, \quad \textbf{(4.1)}$$

where A, B, C, D are the “ray” matrix elements for one complete round trip—starting and ending on the chosen reference plane, e.g., at the center of gain medium. Solving Eq. (4.1) for 1/q_s gives

$$\frac{1}{q_s} = \frac{(D-A) \pm \sqrt{(D-A)^2 + 4BC}}{2B}. \quad \textbf{(4.2)}$$

For a confined Gaussian beam, the square of the beam spot size ω^2 should be a finite positive number. Recalling that q is related to the spot size ω and the radius of curvature R as

$$\frac{1}{q} = \frac{1}{R} - i\frac{\lambda}{\pi\omega^2 n}. \quad \textbf{(4.3)}$$

Therefore, the radius of curvature R and the spot size ω on the reference plane can be obtained from Eqs. (4.2) and (4.3)to be [1],

$$R = \frac{2B}{D-A}, \quad \textbf{(4.4)}$$

$$\omega = \left(\frac{\lambda}{\pi n}\right)^{1/2} \frac{(|B|)^{1/2}}{[1-[(D+A)/2]^2]^{1/4}}. \quad \textbf{(4.5)}$$

We plot the 2ω at gain medium versus cavity length in Fig. 4.4,

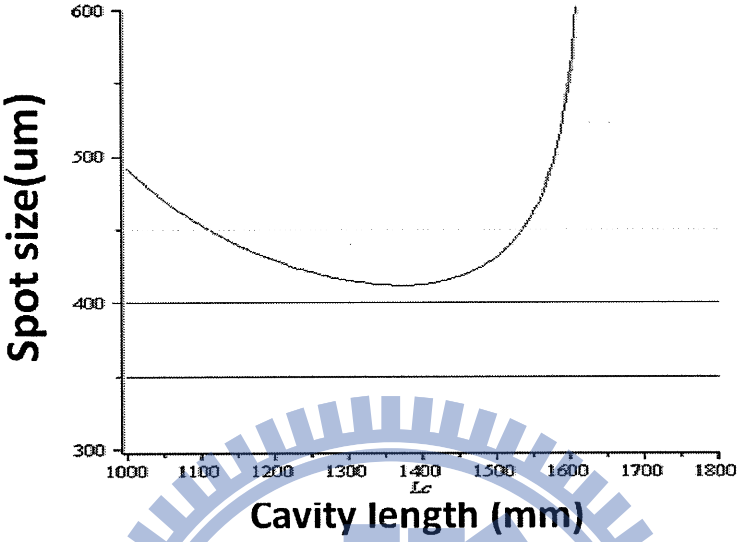

Fig. 4.4 Simulation spot size at gain medium vs. cavity length

The criteria of soft aperture which is the spot size of cold cavity slightly larger than pumping spot size (about 400 um) [2] had been satisfied. So the Kerr-lens mode-locking could happen in our experiment setup.

4-2 Independent variables versus QML effect

4-2.1 Location of AOM in the cavity

By placing the AOM at different locations in the cavity, we found that QML can be achieved in different positions in the cavity even with non-multiple cavity length of 164 cm(Figs.4.5~7).

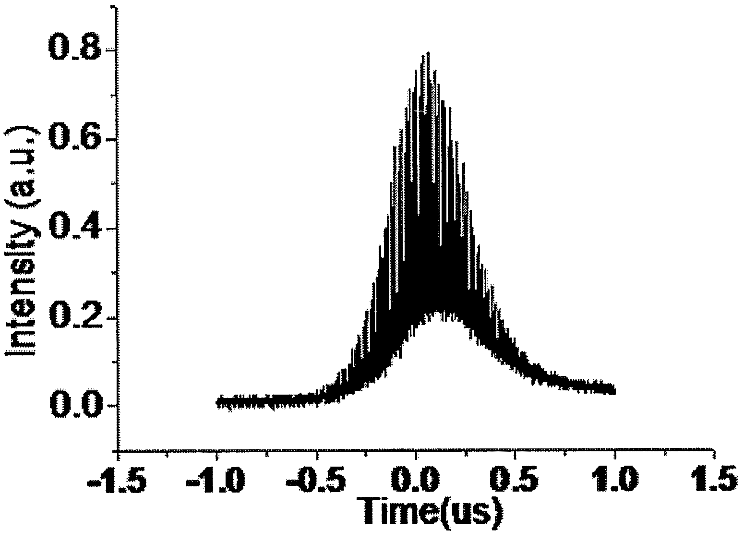

Fig. 4.5 QML in 163cm cavity, 50 kHz AOM MF, front position

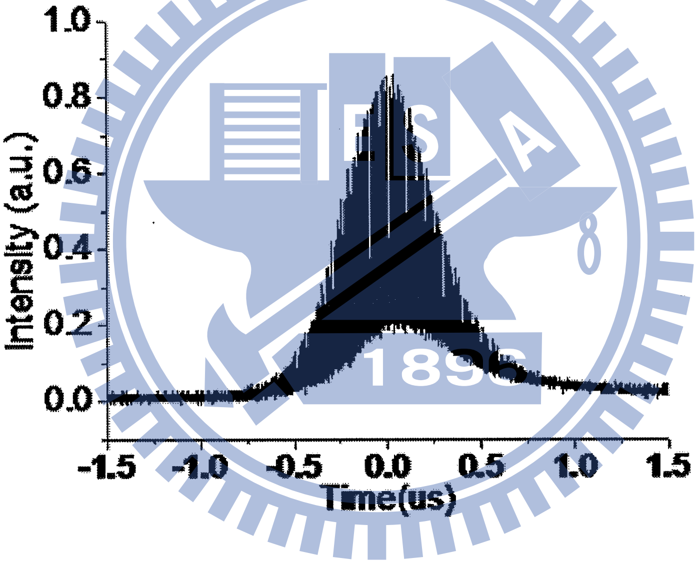

Fig. 4.6 QML in 163cm cavity, 50 kHz AOM MF, mid position

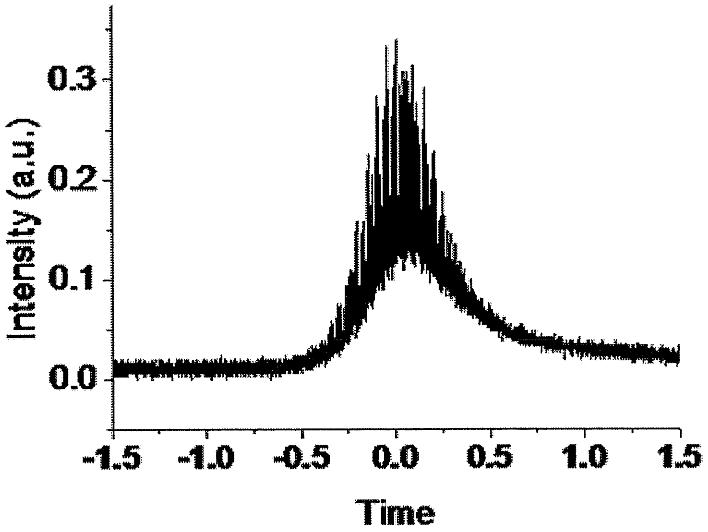

Fig. 4.7 QML in 163cm cavity, 50 kHz AOM MF, rear position.

However, we found the rear position is not well QML compare to the front and mid positions. The possible explanation for this phenomenon could be the divergence angle of the cavity beam at AO inserted at the rear location of cavity is larger than the deflection angle of the used AO modulator. The calculated divergence angle is shown in Table 4.1.

@163cm Cavity	Divergence angle	Spot size@Diameter
Front (10cm)	**2.548 mrad**	**531um**
Mid (40cm)	**1.632 mrad**	**829um**
OC (160cm)	**7.957 mrad**	**170um**

Table 4.1 Divergence angle at different location of AO.

4-2.2 AO modulation frequency and cavity length

AO modulation frequency, which is directly correlated to the repetition rate of Q-switch, plays an important role in active-QML achieved by AO modulator. From our experimental data, we may conclude that the width of Q-switching pulse becomes wider as the AOM MF increases,. Furthermore, from Fig. 4.8, the QML get worse significantly when the cavity length is longer than the stable region of laser cavity, which is around 160 cm in our experiment.

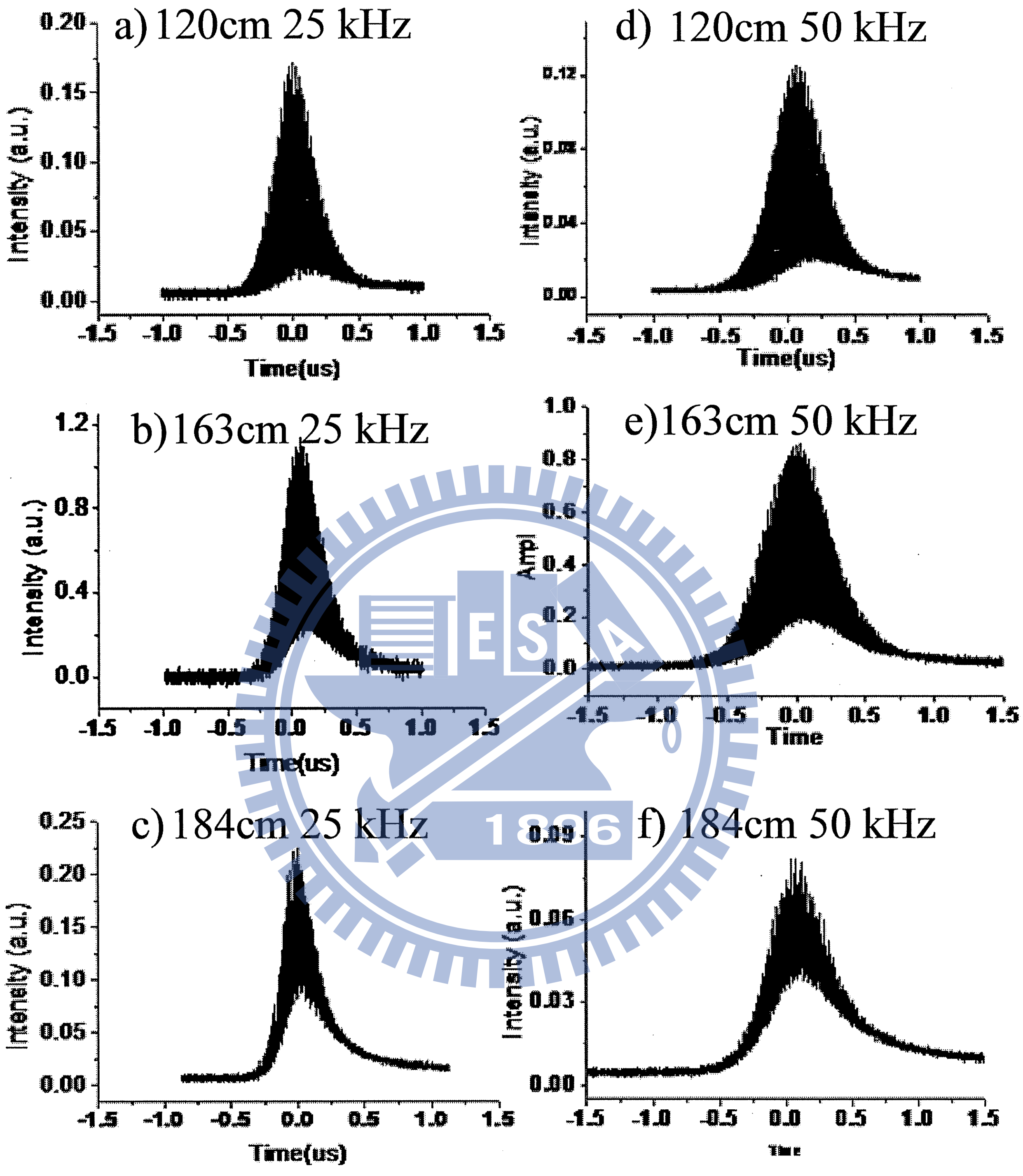

Fig. 4.8QML in different cavity length and different AOM MF

4-2.3 Dependence of pump power

By increasing the pumping power from 7W to 15W, the modulation becomes deeper, and the pulse width also reduces from 0.88 to 0.49 μs as well (Fig. 4.9). It can be explained by Kerr-lens effect, which is increased with increasing pumping power. The increasing soft aperture effect at Kerr medium, which is Nd:LuVO$_4$crystal in our experiment, under stronger pumping should increase the modulation depth.

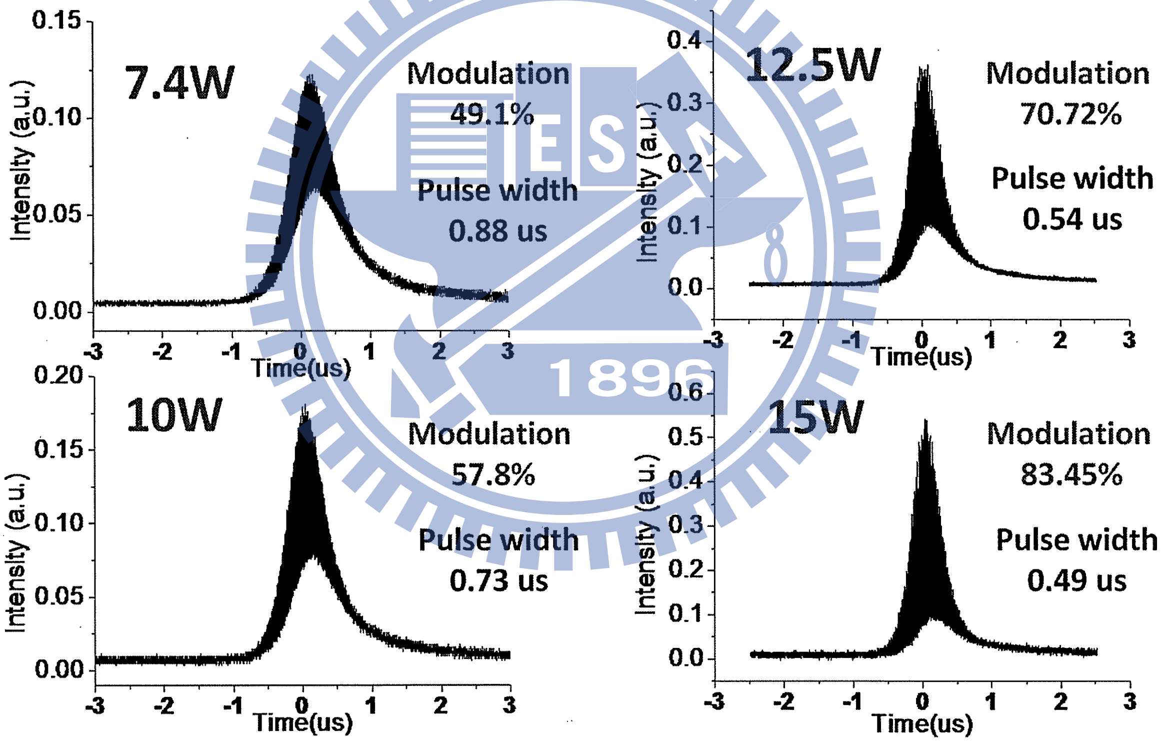

Fig. 4.9 QML in different pumping power

4-3 Location inside cavity and AO modulation frequency versus output power

With different location inside the cavity, especially in the middle and rear positions, there are significant different responses when we increased the AOM MF. Figure4.10 shows that the difference between the middle and rear positions decreased when the AOM MF increased. Furthermore, in Fig. 4.10we discovered that the increasing trend of average output power at the rear position is also different from those of the front and middle positions. As the output powers at the front and middle positions increase in a saturation way, whereas it still linearly increases for AOM at the rear position. Such phenomena could be explained as the following.

At the rear position, the divergence angle of the cavity beam at AO [shown in Table 4.1]is larger than the deflection angle of the used AO modulator.This also explained the high average output power at low modulation frequency and gave a good reason to the linear-like increasing average output power when we increased our AOM MF.

According to Table 4.1, we also found that even with large differences in spot size and divergence angle at the front and middle positions, the trend of increasing average power is basically the same that implies the mode locking is more likely to be induced by other components in the laser cavity such as in the gain medium.

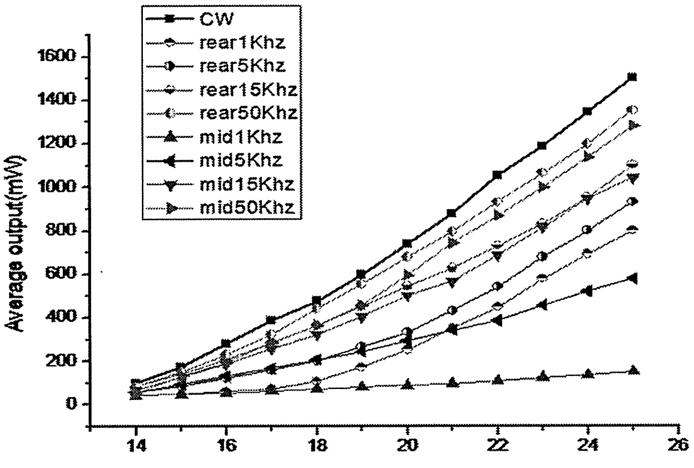

Fig. 4-10 Average output power versus AOM MF and location inside cavity

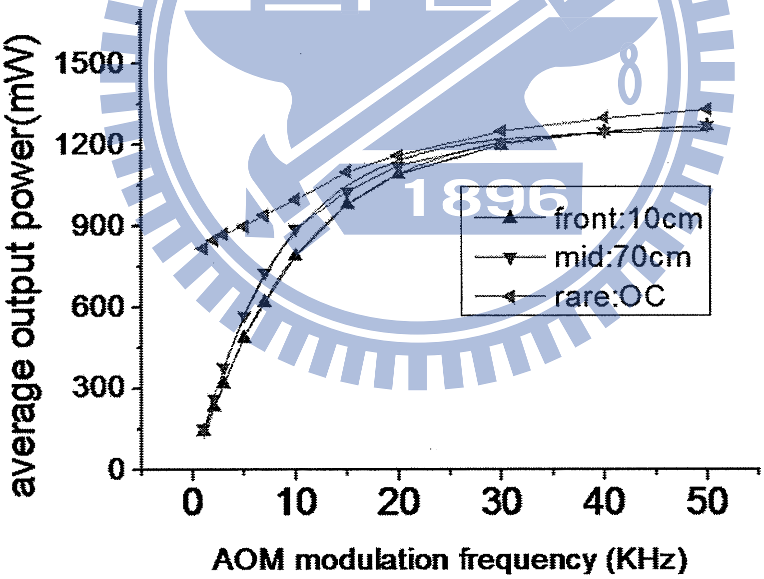

Fig. 4.11 AOM modulation frequency versus average output power

Fitting the Fig.4.10, by using equation (4.6)

$$y = A(1 - e^{-B \times f}), \tag{4.6}$$

where B is a decay constant, and f is our AO modulation frequency. The fitting result of

Bis 96~120 μs, which matches well with the upper state lifetime of Nd:LuVO$_4$. It also explained the reason why 10 kHz AO modulator frequency was widely applied in Nd-doped crystal pulse laser. The upper state life time of some common Nd-doped crystals are shown in Table 4.2.

Nd doped crystal	**Nd:YVO4**	**Nd:GdVO4**	**Nd:LuVO4**
Upper state life time	95us	100us	95us

Table 4.2 The upper state life time of some common Nd-doped crystal.

4-4 Q-switched peak power and pulse width versus pumping power

Since the peak power is a major parameter in pulsed laser, we also discussed the peak power with respect to the pumping power in this section.

The peak power is defined as

$$\text{Peak power}=\frac{\text{average output}}{\text{repetition rate}\times\text{pulse width}} \qquad \textbf{(3-2.7)}$$

From Section 4.3, we knew the average output increases when we raise the pumping power, and from Section 4.2, we discovered the pulse width decreases when we raise the pumping power. According to Eq. (4.7), if we fixed the repetition rate of AOM, the peak power increased rapidly.

The increasing trend of average output for different cavity lengths is also demonstrated in this section. The following figures are the Q-switch pulse widths and peak powers as a function of pump power under different cavity lengths of 99cm, 120cm, and 150cm,respectively.

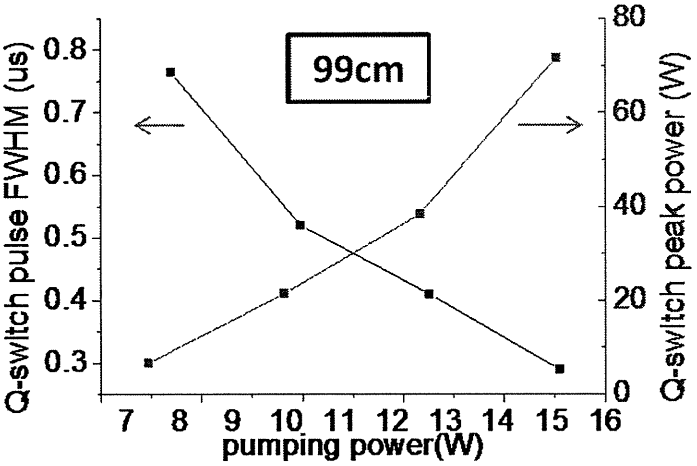

Fig. 4.12 Q-switch pulse width and peak power versus pumping power at 99cm cavity

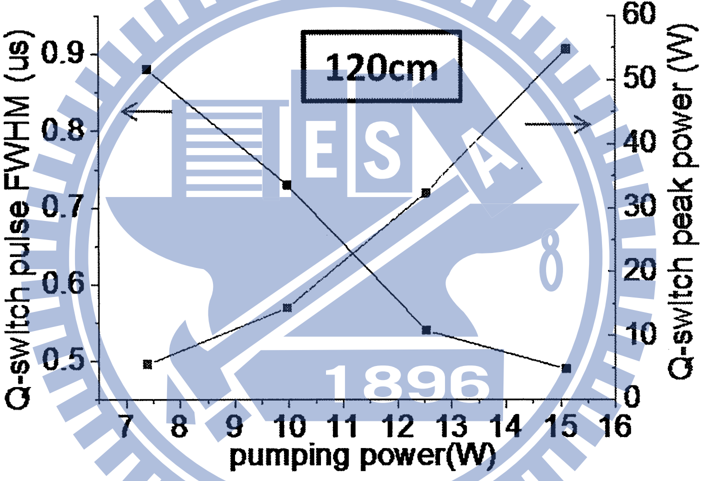

Fig. 4.13 Q-switch pulse width and peak power versus pumping power at 120cm cavity

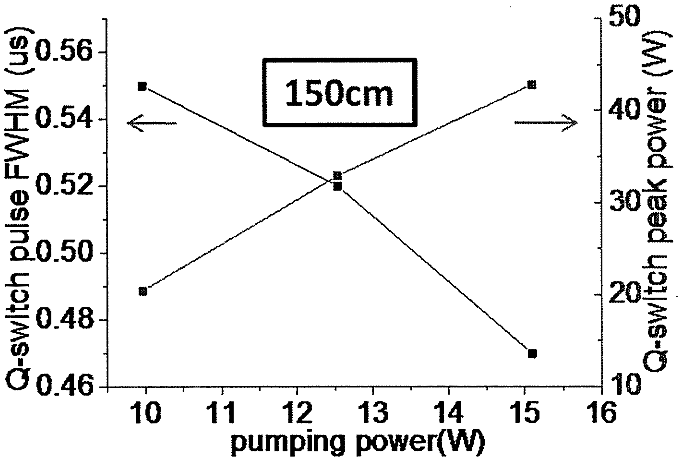

Fig. 4.14 Q-switch pulse width and peak power versus pumping power at 150cm cavity

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Chapter 5 Conclusions and Perspectives

5-1 Conclusions

We have demonstrated an actively Q-switching and mode-locked c-cut $Nd:LuVO_4$ laser by AOM, in which the match of AOM RF and cavity length is NOT a necessary criterion to achieve QML. We obtained the highest pulse energy 184uJ of each Q-switched envelope at 15 W pump power with AOM operated at 1 kHz in this Q-switched mode-locked laser. We also obtained a relationship between upper-state life time of gain medium and optimal modulation frequency of AOM for better peak power, sharper pulse width. Finally, we conclude that the spot size at gain medium may play a more important role rather than at AOM in Q-switching induced mode-locking through self-focusing effect.

5-2 Perspectives

There are still many works needed to be accomplished in the future. We can consider modifying the rate equation by adding Kerr-lens effect to understand Q-switching and mode-locked process. In addition, supercontinuum can be generated by using the QML pulses. Furthermore, the high peak power excitation is convenient for stimulating the carriers in photonic materials and low repetition rate is also essential for preventing thermal heating effect. Therefore, the light source built here is quite suitable for material characterizations such as Z-scan and pump-probe spectroscopy.