Theoretical calculation and experimental study of acousto-optically Q-switched CO_2 laser

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Abstract: Using resonator inserted with acousto-optically modulator, the experiments of the compacted CO_2 laser were performed with Q-switch. According to various factors that influenced the output of laser, the theoretical calculation of its main parameters was conducted by Q-switched pulsed laser rate equations. Based on the results, the technical route and approach were presented for optimization design of this laser. The measured peak power of this laser device was more than 4000W and pulsed width was 180ns which agreed well with the theoretical calculation. The range of repetition frequency could adjust from 1 Hz to 100 kHz. The theoretical analyzes and experimental results showed that the acoustic traveling time of ultrasonic field could not influence the pulse width of laser so that it did not require inserting optical lens in the cavity to reduce the diameter of beam. The acoustic traveling time only extended the establishingtime of laser pulse. The optimum working frequency of laser is about 1 kHz, which it matched with the radiation life time (1 ms) of CO_2 molecular upper energy level. When the frequency is above 1 kHz, the pulse width of laser increased with the frequency. The full band of wavelength tuning between 9.2 µm and 10.8µm was obtained by grating selection one by one which the measured spectrum lines were over 30 in the condition of Q-switch.

OCIS codes: (140.34700) Laser, carbon dioxide; (140.3540) Lasers, Q-switched; (140.3600) Lasers, tunable.

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1. Introduction

CO_2 laser can generate emission from 9 μm to 11μm, and this wave band is just at the window of atmosphere for optical transmission, which makes it have great potential application at the field of optical spectroscopy, imaging ladar, environmental detection, space communication and laser-matter interaction [1–3]. This laser usually works under the condition of high repetition frequency and pulsed mode, but in fact currently compacted CO_2 laser is usually implemented with pulsed output by electro-optically Q-switch and mechanically Q-switch. The electro-optically Q-switch commonly utilizes CdTe crystal as switch device which the pulsed frequency can achieve 100 kHz and pulsed width can be compressed to 10s ns. But the electro-optically Q-switch often need high voltage, more complicated techniques and higher cost [4]. Using high speed rotatable chopper or tilting mirror insert into resonator to realize the mechanically Q-switch, which the advantages of this methods are simple structure, reliable stabilization and low cost, moreover, the peak power of laser pulse can achieve to level of kilowatt [5], but cannot obtain high repetition frequency at the same time because of the limitation of chopper rotatable speed and also cannot perform the programmable control of laser pulse. Another method (acousto-optically Q-switched method) is introduced to realize the pulsed output of compacted CO_2 laser in this paper. This method commonly uses acousto-optical modulator to locate into resonator [6]. However due to the absorption coefficient of this device (often made by Ge crystal) was high and made the optical loss in cavity is so great that the running of laser was difficult. Therefore, there are few reports about this subject as we know. According to a set of coupled rate equations of Q-switched pulsed laser, the main technical parameters are calculated and analyzed for this laser, and furthermore the design and experiments are performing after that. The repetition frequency of this laser can be adjusted from 1 Hz to 100 kHz and pulsed width is 180 ns. The peak power of this laser is above 4000W. The full band tuning between 9.2 μm and 10.8 μm is realized by grating and more than 30 spectrum lines are measured when works under the pulsed condition.

2. Experimental setup

2.1 AO Q-switch

AO Q-switch is the key component of laser, which its principle is the refraction index of crystal changed by using ultrasonic wave as it is transmitting through crystal. The crystal with periodic variation of the refraction index is as the same as a phase grating. When optical beam propagates this crystal, it will create a diffractive wave to realize the optical beam deflection i.e. Bragg diffraction, as Fig. 1. The ultrasonic wave is generated by radio frequency (RF) signal with several tens MHz through AO transducer. Therefore, whether the optical beam is in the condition of deflection or not is totally determined by RF signal controlled by TTL level. When the TTL level is located in high level, the ultrasonic equivalent phase grating will make the optical beam deflection. The deflective angle can completely make the optical beam escape the resonator, which the resonator is in the state of high loss and low Q value. The resonator cannot form the oscillation which means the Q-switch “close” laser. When the TTL level is laid on low level, the RF signal suddenly stops and the ultrasonic field in the Q-switched crystal disappears. This means the switch “open” and the resonator resumes the high Q value with oscillated optical beam output. Accordingly, Q value alternates one time that will generate a Q-switched pulse output from laser. At the same time, if the TTL level is carried out an encoded control, it will realize the encoded pulses output of laser. The acousto-optic medium of AO modulator used in our experiment is Ge single crystal which the single pass transmittance is 90% for the wavelength 10.6 μm. Its center frequency is 40 MHz and using Bragg diffraction vertical incident method. The first order diffraction efficiency of polarized light is about 80% in horizontal direction and the optical aperture is $6 \times 10\ mm^2$.

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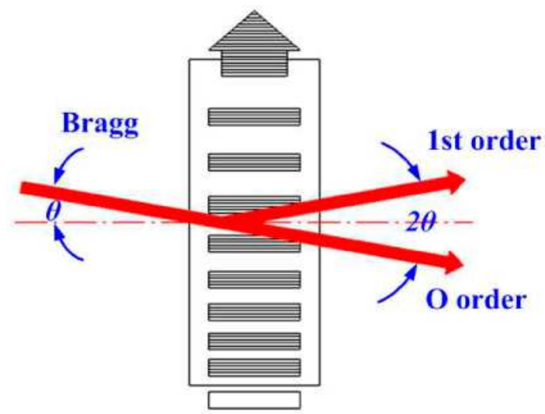

Fig. 1. The scheme of Q-switch

2.2 Laser

The photo of laser and its principle scheme is as Fig. 2.The laser resonator adopts the half external cavity with direct current discharge gain area, which oscillates in first order of grating and output in zero order as be showed in Fig. 2. The length of cavity made by glass tube with water cooled pipe is 1.2 m, the inner diameter is 8 mm, the gain area length of discharge tube is 800 mm and gas pressure is 3.3 kPa. The gas ratio is Xe:CO_2:N_2:He = 1:3:5:21, the curvature radius of mirror is 2.5 m and its reflectivity is 98.5%. The Brewster window is made by ZnSe material and the metal engraved grating is 120 lines/mm, first order reflectivity is 70%. The acousto-optically Q-switcher is placed between the Brewster window and the grating. An iris aperture is inserted in the resonator. The grating is installed on the precise rotating stage which the wavelength tuning is implemented through rotating it.

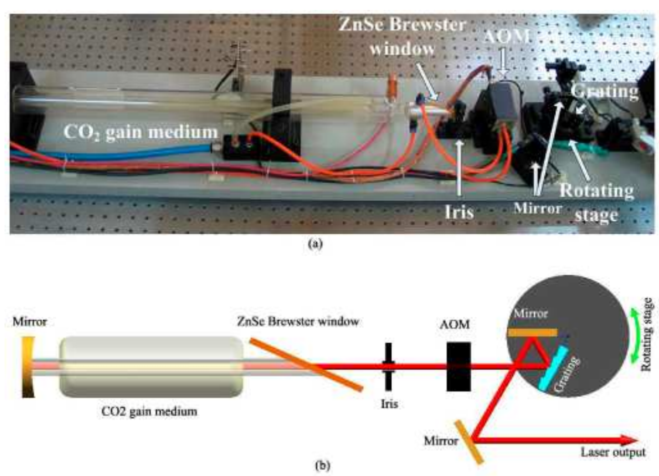

Fig. 2. Experimental setup of programmable acousto-optically Q-switched CO_2 laser

In order to maintain the direction of output beam when the wavelength is tuning, the laser directional output system is designed by using the principle of optical corner reflector which the grating and the mirror are fixed onto the same revolving stage and make them to be coaxial (as Fig. 2).

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3. Laser rate equations and analyzes for Q-switch

3.1 Rate equations

Based on the theory of Q-switched CO_2 laser, the set of coupled differential equations can be written as [7,8]:

$$\frac{d\phi}{dt} = (n_{J'} - n_{J''} - 1)\phi + \frac{n_{J'}}{N_{th}^{V}}. \quad (1)$$

$$\frac{dn_{J'}}{dt} = (n_{J''} - n_{J'})\phi + (P_{J'}n_{v'} - n_{J'})k_{J'}. \quad (2)$$

$$\frac{dn_{J''}}{dt} = (n_{J'} - n_{J''})\phi + (P_{J''}n_{v''} - n_{J''})k_{J''} - n_{J''}k''. \quad (3)$$

$$\frac{d(n_{v'} - n_{J'})}{dt} = (n_{J''} - P_{J'}n_{v'})k_{J'}. \quad (4)$$

$$\frac{d(n_{v''} - n_{J''})}{dt} = (n_{J''} - P_{J''}n_{v''})k_{J''} - (n_{v''} - n_{J''})k''. \quad (5)$$

Where ϕ is the number of photons in the laser mode, $n_{J''}$ is the population of the upper laser level, $n_{V'}$ is the population of the upper 001 vibrational energy level, $n_{J''}$ is the population of the lower laser level, $n_{V''}$ is the population of the lower (100, 200) vibrational energy level, p_J is the initial Boltzmann distribution, k_J is the rotational relaxation rate, and k is the relaxation rate of the (100, 200) population into other vibrational modes. All populations are scaled by the value N_{th}^{V} and all rates are scaled by the cavity lifetime $t_{c'}$ .We have assumed that the rotational relaxation is random that the initial Boltzmann distribution function P_J is shown as [9]:

$$P_J = \frac{(2J+1)}{Q_{rot}} \exp[\frac{-hcBJ(J+1)}{kT}]. \quad (6)$$

Where Q_{rot} is the rotational partition function and B is rotational constant (m^{-1}).The initial total population of all rotational levels in the 001 vibrational mode can be related to the population of the upper laser level by the relation:

$$n_{v'} = \frac{n_{J'}}{P_J}. \quad (7)$$

The spontaneous emission rate into the laser cavity mode is given by $1/N_{th}^{V}$ times the population of the upper laser level when scaled as given above. The rate at which photons escape from the laser cavity is given by $c\overline{\alpha}$, and $\overline{\alpha}$ can be written as:

$$\overline{\alpha} = \frac{\ln(1/T_{TOT})}{2L}. \quad (8)$$

Where T_{TOT} is the total coupled transmission, L is the cavity length. Therefore the peak power is given by:

$$P_{out} = \phi h\nu c\overline{\alpha}_{out} N_{th}^{V}. \quad (9)$$

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According to the relative relaxation rate of CO_2 laser [10–12] and the experimental results of laser, the calculated parameters of this laser are given as: $N_{th}^{V} = 1.02 \times 10^{15}$, $P_J = 0.015$, $t_{c'}$ = 20ns,δ = 20%, ϕ_0 = 2.43 × 10^{-15}, $k_{J'}$ = $k_{J''}$ = 5.78, k'' = 0.072, $n_{J'}\big|_{t=0}$= 0.88, $n_{v'}\big|_{t=0}$= 58.67, $n_{J''}\big|_{t=0}$=0, $n_{v''}\big|_{t=0}$ =0, J'' = 19, substitute these parameters into Eqs. (1)-(5), and using Runge-Kutta method for numerical calculation, which the calculated pulse is shown in Fig. 3. The calculated establishing time of Q-switched pulse is 2.5 μs, the pulse length is 200 ns and the peak power of pulse is 3443 W.

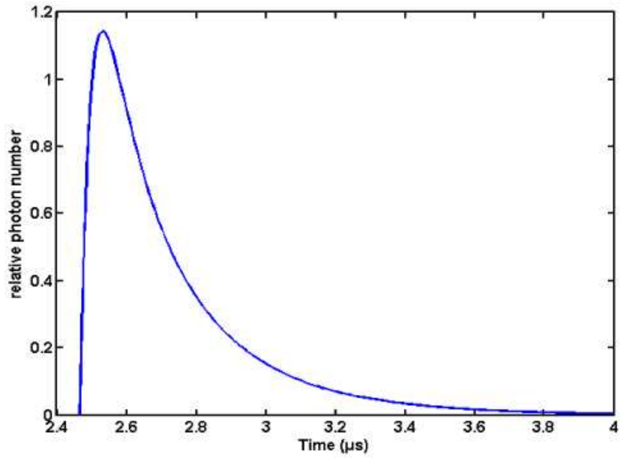

Fig. 3. Photon number in the laser cavity versus time.

When the laser is operated in the Q-switched mode, the small signal gain and relaxation rates can be measured. The establishing time and rise time greatly depend on the gain-loss ratio. When laser starts to work, the irradiance is small and the depletion of the upper level is negligible. From reference 8, the pulse formation can be written as:

$$\Phi_P(t) = \Phi_P(0)\exp\left(\left\{2\gamma_0 l - \ln\left[\frac{1}{R_G T_C^2(1-T_0)}\right]\right\}\frac{ct}{2L}\right). \tag{10}$$

Where R_G is the reflectivity of the grating, T_C is the transmission of the intracavity optical elements, T_0 is the transmission of the output coupler, L is the length of optical cavity, *l* is the length of gain media, c is the velocity of light, $\Phi_P(0)$ is the initial number of photons in the mode that emanate from the spontaneous emission. Substituting the laser parameters into formula (10), we obtain the relation between the establishing time of laser pulse and the transmission in cavity as in Fig. 4. With the increasing transmission in cavity, the establishing time of laser pulse decreases greatly.

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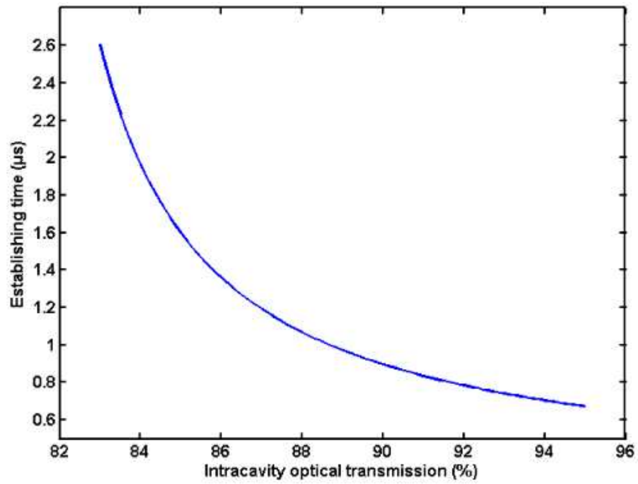

Fig. 4. Transmission of intracavity optical elements versus establishing time of laser pulse.

3.2 Analyzes of Q-switch

The effect of Q-switch in the calculation of the rate Eqs. (1)-(5) is simplified as a step function (as Fig. 5(a)). But in fact the effect of Q-switch more likes a linear function (as Fig. 5(b)). Therefore, the influence of the open time of Q-switch to time response of laser pulse needs to be taken in account. Assuming the oscillation threshold of laser is at t = 0, then $t = t_s$ can be referred to the period from maximum cavity loss (point A) to minimum (point B), which it is equivalent to the opening time of Q-switch. The difference between the actual switching linear function and the ideal step function is dependent on t_s. When $t_s = 0$, it is in the state of the ideal function. Through analyzing physical process of Q-switched laser, if t_s is small enough ($t_s \to 0$), the theoretical results can predict the actual results. Therefore, there must be a characteristic time t_d, if $t_s \le t_d$, the solutions of the rate equations can predict the output behavior of laser pulse. The physical process of the linear function is as follows: if $t_s \ge 0$, the Q-switched pulse begins to establish. But because of the limitation of the linear function, the cavity loss changes gradually. In this stage, if the gain less than the loss, no laser oscillation is generated in the resonator until the threshold is reached ($t_s = t_d$). The variation of Q value in the cavity induces the gain more than the loss, which makes the Q-switched pulse really start to establish and form the output according to the prediction of the rate equations. Thus it can be seen that if the opening time t_s of Q-switch less than the characteristic time t_d, both the linear function and the step function have no influence on the pulse width of laser output. The difference between them is only that the linear function increases the establishing time of pulse. The propagation velocity of ultrasonic wave in Ge crystal is 5900 m/s, which means that the opening time for the optical beam with 5 mm diameter should be 0.85 μs. Thus, the establishing time of pulse showed in Fig. 3 and Fig. 4 should add the corrected value 0.85 μs. Based on above analyzes, if AO modulator is placed inside the resonator, the design of Q-switched pulse laser need not consider the problem of the influence of the acoustic traveling time to the pulse width of laser output so that the requirement of the compressing system of beam diameter is not necessary.

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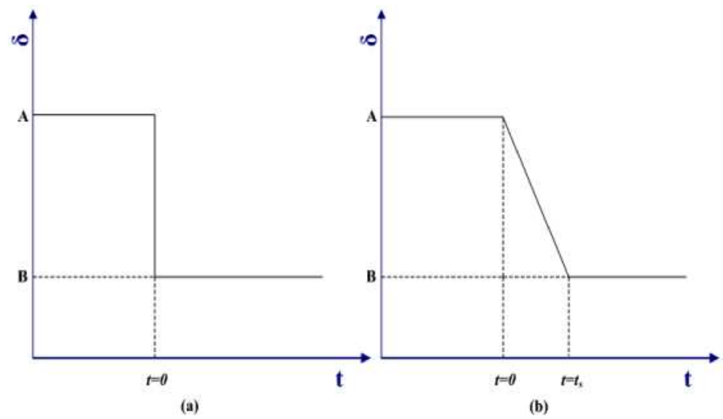

Fig. 5. Formation of Q-switch: (a) step function; (b) linear function.

4 Experimental results and discussions

The experiments firstly illustrate the relation between the acoustic traveling time and the pulse width. In order to compress the pulse width, the general method is using lens to focus the beam into AO crystal to decrease the acoustic traveling time. According to the principle of AO modulator, the angle of divergence of the acoustic beam and optical beam need to be matched each other for fully utilizing the acoustic energy and optical energy. The focal length of lens with satisfying this matching condition is calculated by following formula as:

$$f = \pi dD / 4\lambda, \quad d = 2.55v / f_{AO}. \tag{11}$$

Where d is optimum matching beam diameter after focus, v is the propagation velocity of acoustic wave in AO crystal, f_{AO} is the modulating frequency of driver, D is the beam diameter on the lens and λ is the wavelength of laser.

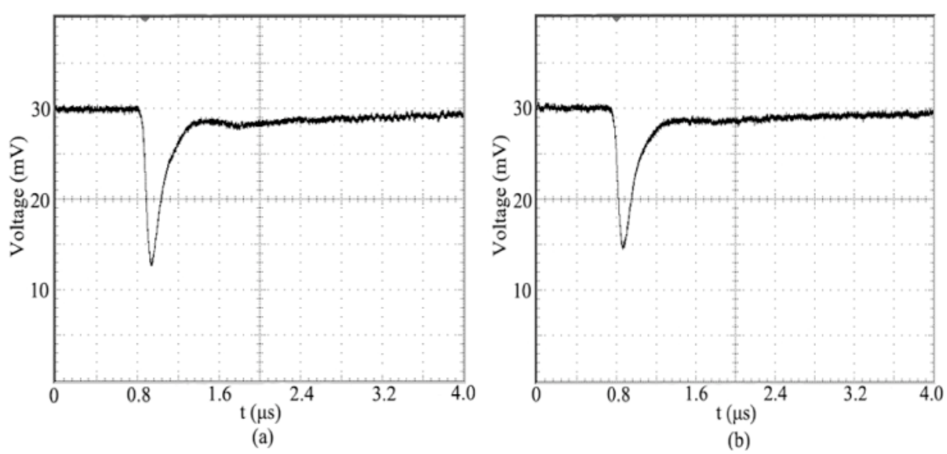

Fig. 6. Diagrams of laser pulse waveform for the different acoustic traveling time: (a) without the lens; (b) with the lens.

Based on the formula (11), a pair of ZnSe lens (f = 100mm) is inserted into the resonator in the experiments, which symmetrically place both sides of the Q-switched crystal. The experimental results show that the beam diameter less than 0.5 mm through the crystal by using ZnSe lens. The corresponding opening time is less than 85 ns. Without ZnSe lens, the beam diameter in the crystal becomes 5 mm, which the opening time is 850 ns. However, the both pulse widths are almost same (shown as Fig. 6). This shows that the above theoretical

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analyzes are correct, which it no need to consider the influence of the acoustic traveling time if the Q-switch is inserted into the cavity. For the Q-switched pulse width in the cavity, the effect of switching gain induced by the variation of inverted population is overwhelming the acoustic traveling time of AO crystal. The meaning of this experiment is to decrease the number of optical components in the cavity, i.e. it decreases the insertion loss and improves the output optical beam quality.

The discharge current of laser is from 8 mA to 16 mA, and maximum output power is 22 W. When inserting the AO modulator (AOM), the maximum output power is decreasing to 7.5 W. The output laser mode is TEM_{00}. The pulsed frequency range is from 1 Hz to 100 kHz. The pulsed waveform of 10.6 μm with repetition rate 1 kHz measured by HAMAMATSU P3257-30 MCT detector is shown as Fig. 7. The output pulsed width is about 180 ns as shown as Fig. 7(a) (channel 2) and channel 1 is TTL trigger signal. The left waveform of channel 2 is RF interference signal of AOM driver, the pulsed establishing time is 2.7 μs and the vanishing time of radio frequency signal is 200 ns as shown in Fig. 7(a). The delay time between the RF signal and the TTL trigger signal is around 150 ns. At that time the measured average power is 0.65 W which can calculate the pulsed peak power is 4062W. The output stability of laser is quite well in high repetition rate, which the pulsed amplitude difference is smaller than ± 10% as shown in Fig. 7(b).

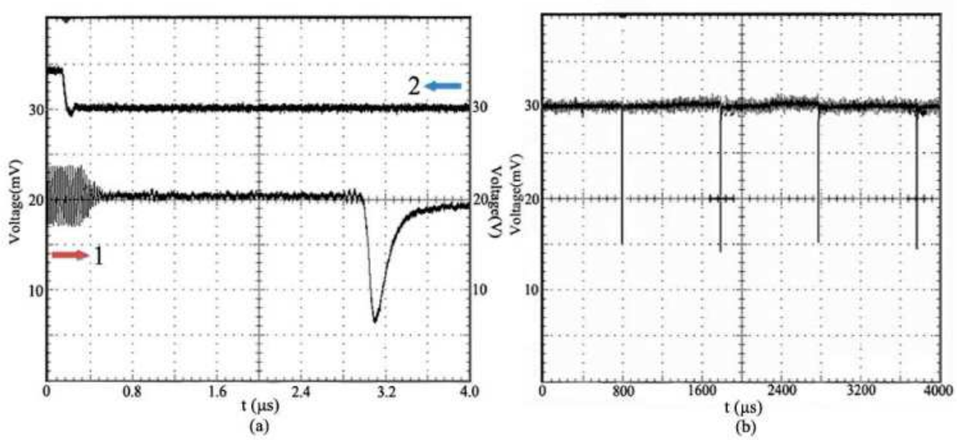

Fig. 7. Laser pulse waveform.

The relation between the peak power and the pulse width is shown as Fig. 8. It shows that the peak power of laser pulse is almost the same value less than 1 kHz, and if more than 1 kHz it appears to slowly descent. If more than 10 kHz, the descent begins to accelerate. The corresponding pulse width changes little if less than 1 kHz and more than 1 kHz, the pulse width increase, but the increasing relative speed are smaller.

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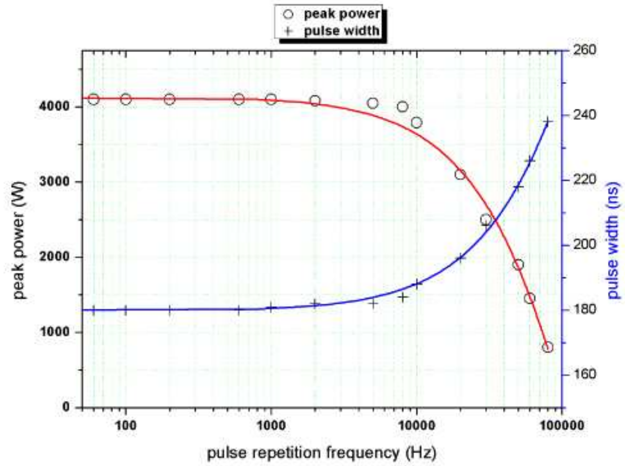

Fig. 8. Peak power and pulse width of laser versus the pulse frequency.

From above experiments, when the frequency less than or equal to 1 kHz, the peak power and the pulse width can achieve the max and minimum respectively. When more than 1 kHz, both values will get worse, which shows that the optimum working frequency is in range of 1 kHz. The repetition of 1 kHz is equivalent to the pulse interval of 1 ms which fits well with the upper energy life time of CO_2 laser. This situation can guarantee the upper energy level to accumulate enough particle number in the working material of CO_2 laser and thus decreasing the excessive spontaneous radiation loss. Otherwise, it can obtain the maximum availability of population inversion under the certain peak power of laser.

When the repetition rate is 50 kHz as shown in Fig. 9, the comparable pulsed waveforms are obtained through adjusting changeable iris in the same condition, which the loss in cavity greatly influences the establishing time of laser pulse. In Fig. 9(a) the establishing time is 4.0 μs and in Fig. 9(b) the establishing time is 2.7 μs. Comparing Fig. 9(a) and Fig. 9(b) also shows that the output average power and peak power of laser have changed greatly (almost one time in difference), but relatively small influence to pulsed width of laser.

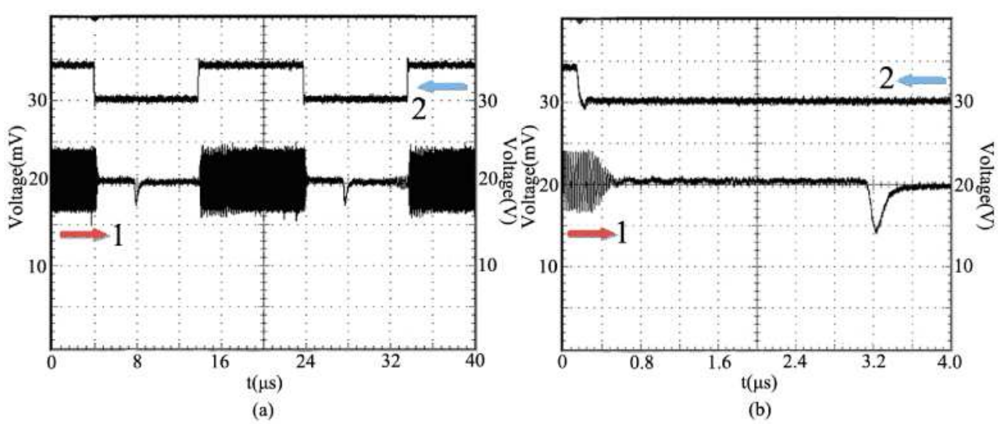

Fig. 9. Laser pulse waveform, (a) optical iris diameter Φ = 4 mm; (b) optical iris diameter Φ = 5 mm.

The establishing time of laser pulse measured is slightly larger than that of theoretical calculations because not concerns about the actual loss increasing caused by the heat influence when operation in the calculations, especially the influence of AO crystal. The AO crystal adopted by our experiments is Ge crystal with type TSG40-1, which its disadvantages

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not only have larger absorption coefficient (absorption coefficient 0.03 cm^{-1}, the length of optical direction 3.7 cm and the calculated single pass absorption 10%), but also have the absorption coefficient increased with the temperature rising. Therefore, the crystal in the cavity will absorb the laser energy and its temperature will rise so that makes the absorption coefficient increase greater. This vicious circle creates great temperature variation. Although the water-cooling system adopted at side of Ge crystal, the temperature of center position is still high for laser beam oscillation. Therefore, the losses in the cavity need to be decreased in the design. The minimum value of best AO crystal is smaller than 6% all over the world. If this kind of modulated crystal is used for Q-switch in the cavity, the formation time of laser pulse will greatly reduce, and the output performance will also improve.

The spectrum lines measured is 35 lines when the wavelength tuning in the condition of Q-switch, which the band of 10P is 13 lines, 10R 12 lines, 9P 7 lines and 9R 3 lines. The output power of laser greatly different in different wave bands since the different laser gains in different wavelength and the grating diffraction efficiency variation.

5 Conclusions

The rate equations can explain and analyze the acousto-optically Q-switched process for the compacted CO_2 laser. The loss in cavity is the main factor to govern the laser operational performance with high repetition rate. Therefore, the high repetition rate, short pulse width and high peak power output for the compacted CO_2 laser are realized by optimizing AO modulator and suitable design of resonator. In the design of laser, the acoustic traveling time is not a key factor, so no need to insert the optical components of compressing beam in the cavity. The optimum working range of this laser is about 1 kHz. This laser can achieve the full spectral line tuning by the grating and programmable output by the TTL signal. This development of this technique will provide an effective technical approach for the applications of high repetition pulsed CO_2 laser.

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