Optics and Lasers in Engineering 50 (2012) 159–164

Contents lists available at SciVerse ScienceDirect

Optics and Lasers in Engineering

journal homepage: www.elsevier.com/locate/optlaseng

Dynamical analysis of acousto-optically Q-switched CO_2 laser

Jijiang Xie [a,*], Qikun Pan [a,b], Ruhai Guo [a], Laiming Zhang [a], Peng Ruan [a,b], Dianjun Li [a], Guilong Yang [a], Chuansheng Zhang [a], Jin Guo [a]

[a] Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, State Key Laboratory of Laser Interaction with Matter, Changchun 130033, China
[b] Graduate School of Chinese Academy of Sciences, Beijing 100039, China

ARTICLE INFO

Article history:
Received 6 April 2011
Received in revised form
28 September 2011
Accepted 28 September 2011
Available online 19 October 2011

Keywords:
Carbon dioxide laser
Acousto-optically Q-switched
Six-temperature model

ABSTRACT

A compacted size high power CO_2 laser has been developed using an acousto-optically (AO) Q-switch. Performance characteristics have been investigated as a function of output mirror transmittance. The theory of six-temperature model for CO_2 lasers has firstly been utilized to analyze the dynamical process in the AO Q-switched CO_2 laser. This theory perfectly explains the behavior of energy transfer between different molecules in laser gain medium, and describes the shape of pulse laser. The calculated pulse waveforms are in good agreement with the experimental result. Both the experimental and theoretical results present that the optimal value of output mirror transmittance is 39%. Under this condition, the measured peak power is 4750 W and pulsed width is 160 ns, which is consistent with the calculations. Six-temperature model is a perfect theory for CO_2 laser kinetics, which will lay a theoretical foundation for the laser optimum design.

1. Introduction

The compacted CO_2 laser with short pulse duration (FWHM), high peak power and high repetition has great potential applications, such as echo-splitting radar, laser cutting, laser-matter interaction, laser spectroscopy, etc. [1–5]. However, the pulse waveform needs to be known for those applications usually, especially for the tail phenomenon of CO_2 laser. Hence, how to describe the details of waveform is a key research subject.

Pulsed discharge and Q-switch are two main technical methods to realize pulse output with repetitions. High-power TEA CO_2 laser utilize pulsed discharge to pump high-pressure working gas (30–100 kPa) [6]. The population of upper laser levels accumulates and the gain exceeds the resonance threshold immediately after pulse discharge, and then a giant pulse is emitted whose peak power is up to MW. With the increase of the repetition rate, the temperature of working gas and the decay rate of upper laser rise quickly, which will limit the laser generation and thus the repetition rate of TEA CO_2 laser is limited to several hundreds of Hz [7]. The working pressure of compact CO_2 laser is low usually (1–20 kPa) and the working gas temperature is easy to limit in a reasonable range under continuous work. This laser usually utilizes Q-switch to realize pulse output, whose repetition rate is affected by the performance of Q-switch, so its repetition rate can reach to several tens of kHz.

In fact, currently compacted CO_2 laser is usually implemented with pulsed output by electro-optically Q-switch and mechanically Q-switch [8,9]. However there are a few research reports about using AO Q-switched method to realize the pulsed output of compacted CO_2 laser presently. The experiment results of the compacted CO_2 laser with short pulse duration and high repetition have been reported by our group and this CO_2 laser utilized resonator inserted with acousto-optical modulator (AOM) to realize Q-switched laser output [10]. The theoretical analysis has been given using the Q-switched pulsed laser rate equations. But the pulsed waveform calculated by the rate equations cannot explain the tail phenomenon. Therefore, the theory of six-temperature model was introduced firstly to analyze dynamical process of AO Q-switched CO_2 laser in this paper [11]. This theory has been utilized to analyze dynamics of TEA CO_2 laser and describe the waveforms of pulse laser successfully [12]. The six-temperature model more perfectly explains the behavior of energy transfer between different molecules in the laser gain medium, and analyzes the influence of gas temperature on output laser. However the rate equations can only explain the particle population transfer between up and down energy level. Therefore the six-temperature model will give a more correct analysis than the rate equations.

The six-temperature model includes many parameters, such as the transmittance of output mirror, the resonator length, the gas ratio, etc. Our laboratory has manufactured a group of ZnSe output mirrors with different transmittances. Performance characteristics have been investigated as a function of output mirror transmittance with an AO Q-switch. Therefore the parameter of transmittance was investigated with six-temperature model in this paper when the other parameters kept invariability. Then the numerical calculations were given for six-temperature model at different transmittances of output mirror. The six-temperature

* Corresponding author. Tel./fax: +86 43186176196.
E-mail addresses: laserxjj@163.com (J. Xie), panqikun2005@163.com (Q. Pan).

0143-8166/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.optlaseng.2011.09.014

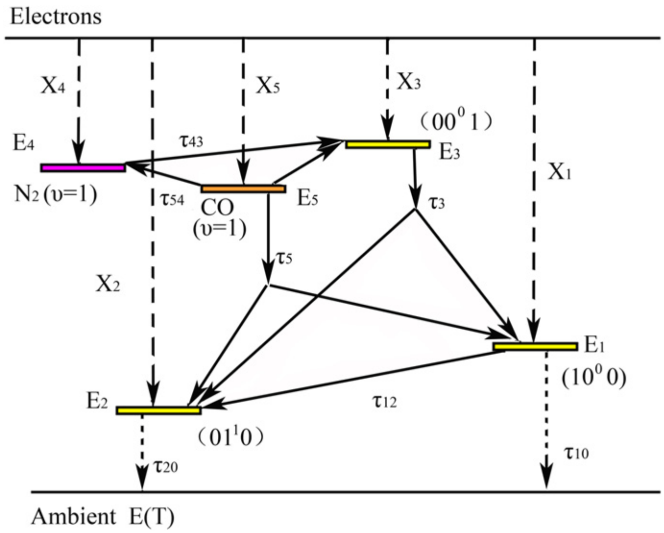

Fig. 1. Schematic energy-level diagram for N_2–CO_2–CO system.

model is presented in the second section. The calculated and experimental results are both analyzed in the third section.

2. The six-temperature model for acousto-optically Q-switched CO_2 laser

Based on the theory of five-temperature model of the dynamics for CO_2 laser [11], the dissociating influence of CO_2 to CO molecules on laser output is concerned. Thus the equivalent vibrational temperature of the CO molecules is taken as a variable quantity of the differential equations for this model. Then the differential equations include six variable quantity of temperature.

In Fig. 1, we present a schematic diagram of the set of processes of electron collision excitation for CO_2, N_2, and CO molecules, all kinds of energy transfer among molecules, and excited emission and spontaneous emission. The distribution of vibrational energy in different vibrational modes can be described by the following equations [11,12]:

$$\frac{dE_1}{dt}=n_e(t)fn_{co_2}X_1h\upsilon_1-\frac{E_1-E_1(T)}{\tau_{10}(T)}-\frac{E_1-E_1(T_2)}{\tau_{12}(T_2)}+\frac{h\upsilon_1}{h\upsilon_3}\frac{E_3-E_3(T,T_1,T_2)}{\tau_3(T,T_1,T_2)}+\frac{h\upsilon_1}{h\upsilon_5}\frac{E_5-E_5(T,T_1,T_2)}{\tau_5(T,T_1,T_2)}+h\upsilon_1\Delta NWI_{\upsilon_0} \tag{1}$$

$$\frac{dE_2}{dt}=n_e(t)fn_{co_2}X_2h\upsilon_2+\frac{h\upsilon_2}{h\upsilon_3}\frac{E_3-E_3(T,T_1,T_2)}{\tau_3(T,T_1,T_2)}+\frac{E_1-E_1(T_2)}{\tau_{12}(T_2)}-\frac{E_2-E_2(T)}{\tau_{20}(T)}+\frac{h\upsilon_2}{h\upsilon_5}\frac{E_5-E_5(T,T_1,T_2)}{\tau_5(T,T_1,T_2)} \tag{2}$$

$$\frac{dE_3}{dt}=n_e(t)fn_{co_2}X_3h\upsilon_3+\frac{E_4-E_4(T_3)}{\tau_{43}(T)}-\frac{E_3-E_3(T,T_1,T_2)}{\tau_3(T,T_1,T_2)}+\frac{h\upsilon_3}{h\upsilon_5}\frac{E_5-E_5(T,T_3)}{\tau_{53}(T,T_3)}-h\upsilon_3\Delta NWI_{\upsilon_0} \tag{3}$$

$$\frac{dE_4}{dt}=n_e(t)fn_{N_2}X_4h\upsilon_4-\frac{E_4-E_4(T_3)}{\tau_{43}(T)}+\frac{h\upsilon_4}{h\upsilon_5}\frac{E_5-E_5(T,T_4)}{\tau_{54}(T,T_4)} \tag{4}$$

$$\frac{dE_5}{dt}=n_e(t)(1-f)n_{co_2}X_5h\upsilon_5-\frac{E_5-E_5(T,T_3)}{\tau_{53}(T,T_3)}-\frac{E_5-E_5(T,T_1,T_2)}{\tau_5(T,T_1,T_2)}-\frac{E_5-E_5(T,T_4)}{\tau_{54}(T,T_4)} \tag{5}$$

where n_{CO_2} and n_{N_2} are the number density of CO_2 and N_2 molecules per unit volume, respectively, and $n_e(t)$ is the number density of electrons per unit volume. T_1 is the equivalent vibrational temperature of the CO_2 symmetrical stretching mode. T_2 is the equivalent vibrational temperature of the CO_2 bending mode. T_3 is the equivalent vibrational temperature of the CO_2 asymmetric mode. T_4 is the equivalent vibrational temperature of the N_2 molecules. T_5 is the equivalent vibrational temperature of the CO molecules. Eqs. (1)–(3) describe the variation in the stored energy in unit volume (erg/cm^3) as a function of time in CO_2 symmetrical, bending, and asymmetrical modes. Eq. (4) expresses the time evolution of the stored energy density in unit volume for N_2 molecules. Eq. (5) expresses the time evolution of the stored energy density in unit volume for CO molecules, which are dissociated by CO_2 molecules. f is the non-dissociated fraction of CO_2 molecules. For simplicity f is considered as a constant in this paper (in general f is a function of time, electrical field intensity and electron number density).

By taking the sum of Eqs. (1)–(5) in the steady state, the following equation, which describes the time evolution of the stored energy density in gas mixture CO_2–N_2–He–CO will be obtained:

$$\frac{dE_K}{dt}=\frac{E_1-E_1(T)}{\tau_{10}(T)}+\frac{E_2-E_2(T)}{\tau_{20}}+\left(1-\frac{h\upsilon_1}{h\upsilon_3}-\frac{h\upsilon_2}{h\upsilon_3}\right)\frac{E_3-E_3(T,T_1,T_2)}{\tau_3(T,T_1,T_2)}+\left(1-\frac{h\upsilon_3}{h\upsilon_5}\right)\frac{E_5-E_5(T,T_3)}{\tau_{53}(T,T_3)}+\left(1-\frac{h\upsilon_1}{h\upsilon_5}-\frac{h\upsilon_2}{h\upsilon_5}\right)\frac{E_5-E_5(T,T_1,T_2)}{\tau_5(T,T_1,T_2)}+\left(1-\frac{h\upsilon_4}{h\upsilon_5}\right)\frac{E_5-E_5(T,T_4)}{\tau_{54}(T,T_4)} \tag{6}$$

where the total gas kinetic energy E_k per unit volume is

$$E_k=\left(\frac{5}{2}n_{N_2}+\frac{5}{2}n_{CO}+\frac{3}{2}n_{He}+\frac{5}{2}fn_{CO_2}\right)kT \tag{7}$$

where $n_{CO}=(1-f)\,n_{CO_2}$ is the number density of CO molecules per unit volume.

Taking into consideration the stimulated emission, spontaneous emission, and losses in the cavity yields the equation that describes the time evolution of the cavity light intensity

$$\frac{dI_{\upsilon_0}}{dt}=-\frac{I_{\upsilon_0}}{\tau_c}+ch\upsilon_0\left[\frac{\Delta NWI_{\upsilon_0}}{h}+n_{001}P(J)S\right] \tag{8}$$

where c is the light velocity, h is Planck constant, τ_c is the photon life time in the cavity

$$\tau_c=-\frac{2L}{c(\ln R_1+2\times\ln R_2)} \tag{9}$$

where R_1 is the reflection coefficient of rear mirror, R_2 is the reflection coefficient of the output mirror, L is the resonator length. The expressions of W and S in Eq. (8) are

$$W=\frac{\lambda^2F}{4\pi^2\upsilon_0\Delta\upsilon_L\tau_{sp}} \tag{10}$$

$$S=\frac{2\lambda^2}{\pi A\tau_{sp}}\times\frac{\Delta\upsilon_N}{\Delta\upsilon_L} \tag{11}$$

where λ is the laser wavelength, υ_0 is the laser frequency, $\Delta\upsilon_L$ is the laser transition line width, $\Delta\upsilon_N$ is the laser natural line width, τ_{sp} is the spontaneous emission rate, A is the cross section of the laser beam, $F=l/L$ is the filling factor, and l is the length of gain media.

When the Q-switch is closed, the loss in the cavity is so high that there is no laser output and the laser intensity in the cavity is nearly zero. So the Eqs. (1)–(5) is equal to zero. In the five equations mentioned above, E_1 (the energy per unit volume stored in the CO_2 symmetrical stretching mode), E_2 (the energy per unit volume stored in the CO_2 bending mode), E_3 (the energy per unit volume stored in the CO_2 asymmetrical modes), E_4 (the energy per unit volume stored in the N_2 molecules), and E_5

(the energy per unit volume stored in the CO molecules) are defined respectively by T_1, T_2, T_3, T_4, and T_5. A computer program processed in MATLAB is used to solve the five nonlinear equations. The five temperatures and an estimated ambient temperature are the initial values of the laser after the Q-switch is opened.

After the Q-switch is opened, the transmittance of output mirror is t. Therefore the population number of upper levels falls sharp; the laser oscillates rapidly in a short time, and then engenders a giant pulse output. The mathematical model of Q-switched CO_2 laser consists of seven differential expressions, which are dE_1/dt, dE_2/dt, dE_3/dt, dE_4/dt, dE_5/dt, dE_k/dt, and $dI\upsilon_0/dt$, respectively. The variables in these expressions are T_1, T_2, T_3, T_4, T_5, T, and $I\upsilon_0$.There is six temperature variables in the differential expressions, therefore it is called six-temperature model.

The specific expressions of the seven coupled differential equations are represented by Eqs. (1)–(6) and (8). Based on the Runge–Kutta theory, the seven variables (T_1, T_2, T_3, T_4, T_5, T, and $I\upsilon_0$) can be obtained through solving the differential equations. The laser output power can be obtained from $I\upsilon_0$

$$P_{\text{out}} = -\frac{A}{2}\ln(R_2) \times \frac{1-R_2-\alpha}{1-R_2} \times I(t) \times 10^{-7} \tag{12}$$

where α is the loss coefficient of output mirror. Note: for simplicity we consider α as a constant (in general α depends on thickness, coating and substrate material of the output mirror).

3. Calculated results and experimental analysis

3.1. Numerical calculation of six temperature model

The initial values of Q-switched CO_2 laser have been considered before the Q-switch is opened. Based on the measured results of the laser and related values of the equation parameters, which are shown in Table 1, the six-temperature model is used for calculating the process of dynamical emission in the AO Q-switched CO_2 laser. When the transmittance (t) of output mirror is 18%, 25%, 32%, 39%, 46%, 53% separately, a computer program processed in MATLAB is used to solve the differential equations based on the Runge–Kutta theory. Fig. 2 shows the variation of light intensity in the cavity with time. The light intensity is reduced with increasing of the transmittance gradually. And when the increment of the transmittance is 7 percent, the decrease in light intensity is almost 28 percent. Then the laser pulse waveform is calculated by the Eq. (12) at different transmittances as in Fig. 3, which shows that the influence of transmittance on power is obvious. The laser output peak power is a function of output mirror transmittance when other conditions remain unchanged. The theoretical results show that the peak power of the laser has a maximum following the variety of transmittance, which lay a theoretical foundation for the optimization of laser parameter.

Table 1
Parameters used in the calculations.

Parameter	Numerical value	Parameter	Numerical value
υ_1/c[a]	1337 cm^{-1}	h	6.626×10^{-27} erg s
υ_2/c[a]	667 cm^{-1}	BCO_2[b]	0.4 cm^{-1}
υ_3/c[a]	2349 cm^{-1}	τ_{sp}[b]	0.2 s
υ_4/c[c]	2330 cm^{-1}	λ	10.6 μm
υ_5/c[c]	2150 cm^{-1}	c	2.998×10^{10} cm s^{-1}
X_1[b]	5×10^{-9} cm^3 s^{-1}	M_{CO_2}[c]	$7.3v10^{-23}$ g
X_2[b]	3×10^{-9} cm^3 s^{-1}	M_{CO}[c]	4.6×10^{-23} g
X_3[b]	8×10^{-9} cm^3 s^{-1}	M_{N_2}[c]	4.6×10^{-23} g
X_4[b]	2.3×10^{-8} cm^3 s^{-1}	M_{He}[c]	6.7×10^{-24} g
X_5[b]	3×10^{-8} cm^3 s^{-1}	k	1.38×10^{-16} erg K^{-1}
α[d]	0.01453%		

[a] See Ref. [13].
[b] See Ref. [12].
[c] See Ref. [11].
[d] See Ref. [14].

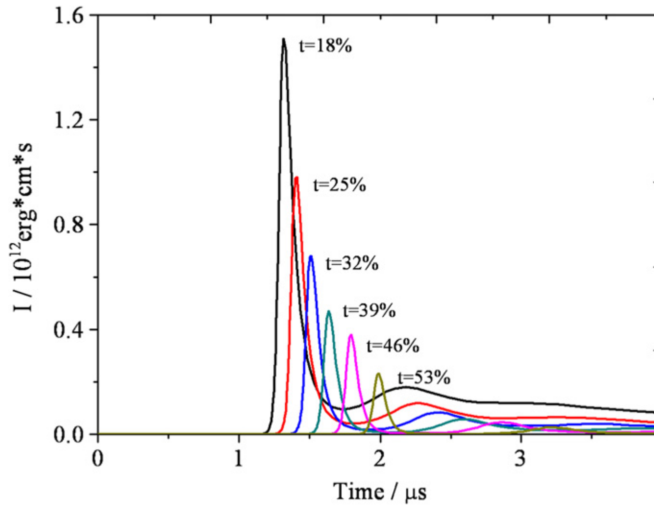

Fig. 2. Light intensity in the laser cavity versus time at different transmittance.

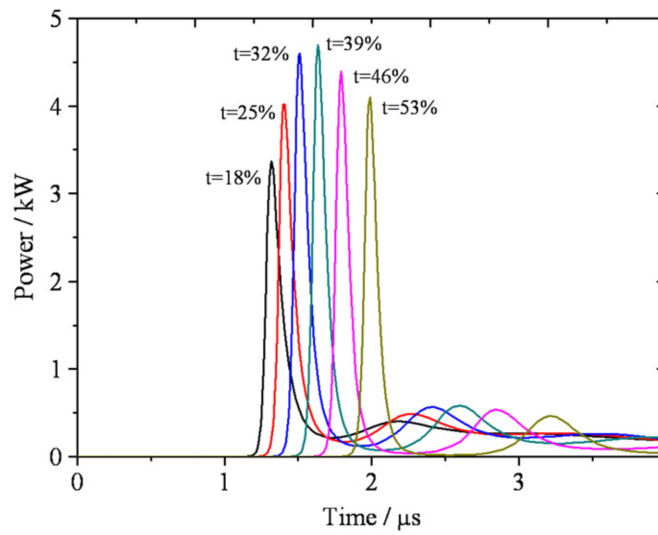

Fig. 3. Output power of the laser versus time at different transmittance.

3.2. Experimental device

The diagram of experimental device is shown in the Fig. 4. The laser resonator adopts the half external cavity with direct current discharge gain area, and the laser is output directly by the ZnSe output mirror. The discharge tube is made by glass with water cooled pipe, the inner diameter is 8 mm, the gain area length of discharge tube is 0.8 m and the mixed gas pressure is 3.3 kPa. The gas ratio is Xe:CO_2:N_2:He=1:2.5:2.5:17.5. The curvature radius of rear mirror is 3 m and its reflectivity is 98.5%.The Brewster window is made by ZnSe material and the length of optical cavity resonator is 1.2 m. The AO Q-switch is inserted between the output mirror and the Brewster window (The AO medium of AOM used in our experiment is Ge single crystal whose single pass transmittance is 90% for the wavelength 10.6 μm. Its center frequency is 40 MHz and it uses Bragg diffraction vertical incident method. The first order diffraction efficiency of polarized light is about 80% in horizontal

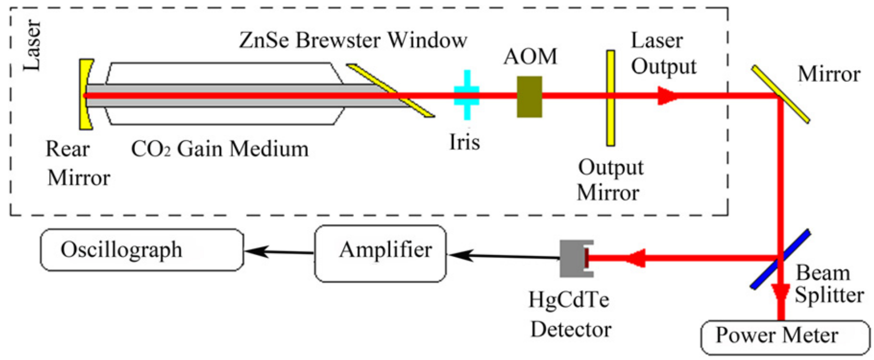

Fig. 4. Diagram of experimental device.

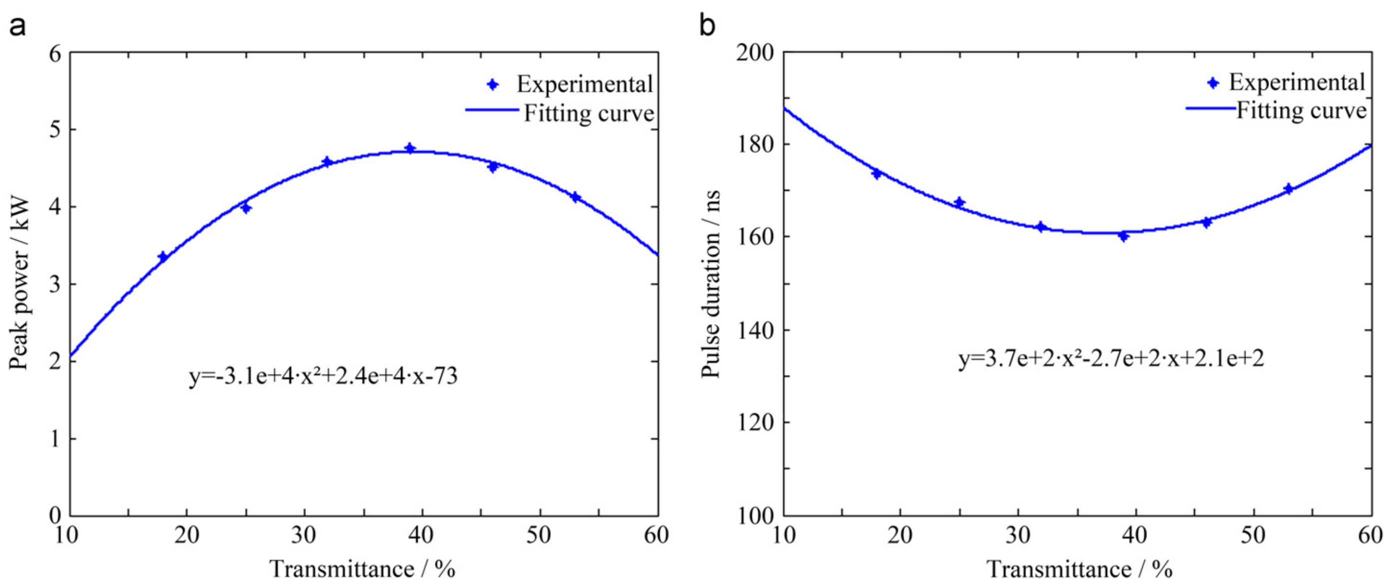

Fig. 5. The fitting curve of peak power (a) and the pulse duration (b) versus the transmittance of output mirror.

direction and the optical aperture is $6 \times 10\ mm^2$). An iris is located between the Brewster window and the AOM. The coated output mirror is made by ZnSe material. The path of laser output will be changed by the mirror first, just as showed in the Fig. 4, and then the laser is divided into two paths by a beam splitter (a coated ZnSe mirror whose transmittance is 30%). A path of laser is accepted by the detector, and then the laser pulse waveform will be displayed by the oscilloscope after enlarged by the amplifier. The other path of laser is monitored by the power meter at the same time.

The AO Q-switch utilizes circulating water cooling system, so the perimeter temperature of AO crystal is almost invariable. At the meantime, some heat absorbed by the AO crystal cannot be decayed immediately, especially at higher pulse repetition rate. Therefore the center temperature of that is increasing immediately. The temperature contrast between the perimeter and center should induce a transversal thermal gradient distribution in the inner crystal, which would change the refractive index profile. The performance of Q-switch would deteriorate when the temperature contrast is large enough, i.e. the laser cannot work with high repetition rate. Besides, the absorption coefficient and deformation of AO crystal will rise with the increase of temperature, which will increase the intracavity laser loss and restrict the peak power. The attenuation of peak power is crucial at high pulse repetition rate (more than 10 kHz) due to the decrease of single pulse energy and increase of pulse duration [10]. Therefore the performance of Q-switch is a significant factor to influence laser output.

3.3. Experimental results analysis

In the experiment, under the working condition of the AO Q-switch, the pulse repetition rate can be tuned from 1 Hz to 100 kHz. The voltage of the bipolar poles is 20 kV, and the input power is 160 W. The relationships between the output mirror transmittance and the peak power as well as pulse duration are researched separately. The transmittances of alternative output mirror are 18%, 25%, 32%, 39%, 46%, 53% separately. At 5 kHz pulse repetition rate, the average power and pulse duration are measured for each mirror independently, and then the peak power of laser is calculated. The quadratic fitting curves of peak power and pulse duration versus the transmittance of output mirror are shown in Fig. 5. The experimental results agree well with that of the six-temperature model theory. The transmittance of output mirror has a significant influence on the peak power and pulse duration of AO Q-switched CO_2 laser, and the optimal transmittance of output mirror is 39% in the experiment.

Just as shown in Fig. 5, when the transmittance of output mirror is 39%, the AO Q-switched CO_2 laser has the best output performance. Under the optimal experiment condition, the Q-switched pulsed laser was detected by a photovoltaic HgCdTe detector with the model of PVM-10.6 made by ZIGO Company of Holland, and the laser waveform could be monitored on a TDS3052B digital storage oscilloscope with 500-MHz bandwidth.

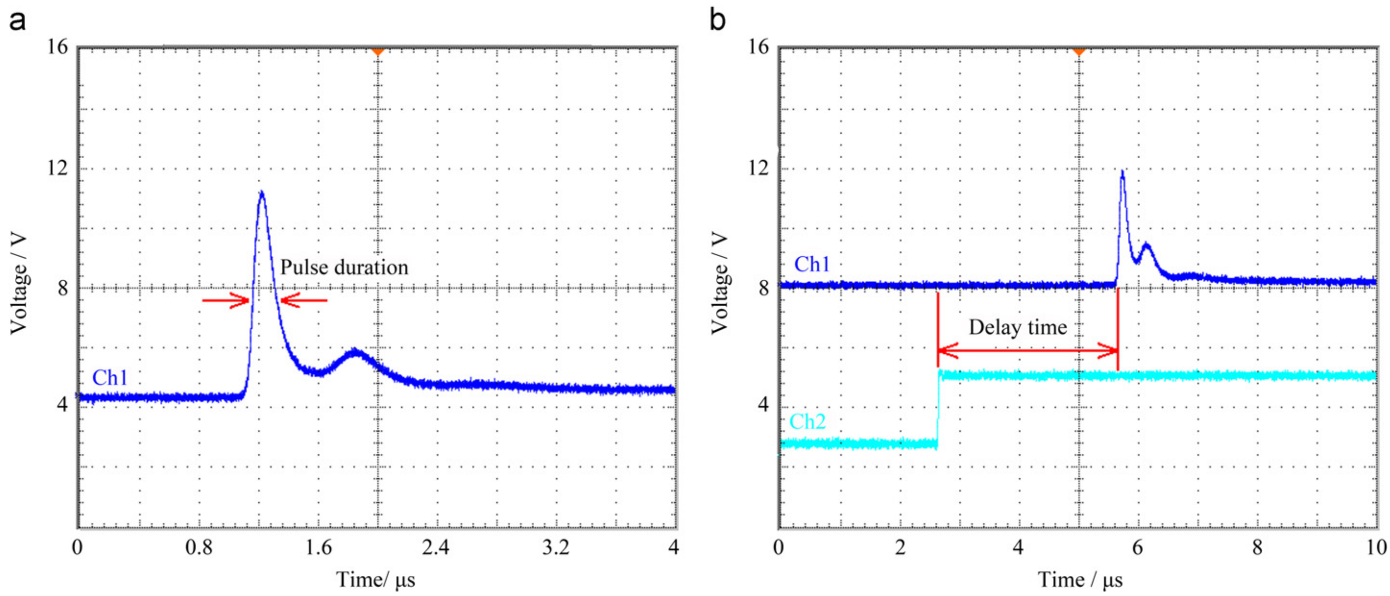

Fig. 6. The measurement shape of the pulsed laser (a) pulse duration and (b) delay time (Ch1 is Laser pulse waveform, Ch2 is TTL trigger signal).

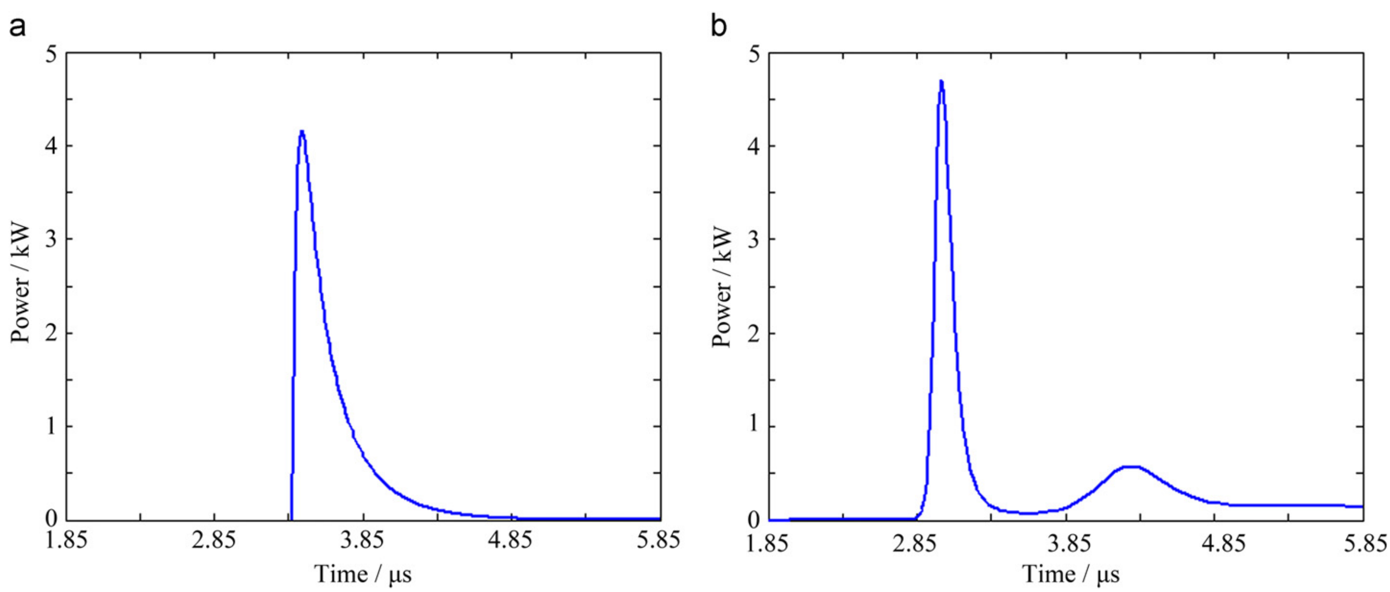

Fig. 7. The theoretical shape of the pulsed laser (a) calculated by rate equations and (b) calculated by six temperature model.

The shape of the pulsed laser is shown in Fig. 6, with a 160 ns pulse duration and a 3 μs delay time. The average power was 1.14 W, which was measured by the power meter with the model of LP-3C made by Bejing WuKe Photo Electricity Company. Thus the output average power of this device was 3.8 W (splitting ratio is 3:7), and the peak power of this laser is 4750 W. Considering the open time of AO Q-switch, the establishing time of laser pulse should be added the corrected value 0.85 μs [10]. Under those conditions, the numerical calculations are shown in Fig. 7.

A conclusion can be drawn by comparing Fig. 6 with Fig. 7. The measured results of peak power, pulse duration and establishing time of laser pulse are in agreement with the theoretical calculations by rate equations as well as six-temperature model. The tail phenomenon is obvious in the calculation by six-temperature model, which is more consistent with the experimental result. The comparison of theoretical calculations and experimental results are shown in Table 2.

Table 2
The comparison of theoretical calculations and experimental results.

Comparing results	Rate equations	Six temperature model	Experimental result
Pulse width/ns	200	166	160
Peak power/kW	4.15	4.7	4.75
Pulse delay Time/μs	3.35	2.9	3
Tail phenomenon	Not obvious	Obvious	Obvious

4. Conclusions

The CO_2 laser with high repetition, short pulse duration and high peak power can be realized by optimizing parameter of transmittance. Under the experimental condition, the quadratic fitting curves of pulse duration and peak power versus the transmittance of output mirror were obtained independently. The results are in good agreement with the theoretical calculations by six-temperature model. Both the theory and experiment present that the optimal value of transmittance is 39% in our works.

Both the rate equations and six-temperature model can explain and analyze the AO Q-switched process of the compacted CO_2 laser. However the six-temperature model more suitable to simulate the waveform of pulsed laser, which obviously explain the tail phenomenon. Therefore the six-temperature model is more suitable to analyze the influence of laser parameters (the transmittance of output mirror, the resonator length, the gas ratio, etc.) on output performance of laser, especially gives the reasonable explanation for the tail phenomenon of CO_2 laser, which sometimes is very important for the performance of TEA CO_2 laser. By choosing the suitable parameters of laser, a waveform with little tail or no tail would be obtained based on the theory of six-temperature model, which will give a reference to optimum design for AO Q-switched CO_2 laser.

Acknowledgment

This work was supported in part by the State key laboratory fund project (no. SKLLIM0902-01), and Science and Technology support project of Jilin Provincial Science & Technology Department (no. 20090358).

References

[1] Kariminezhad H, Parvin P, Borna F, Bavali A. SF_6 leak detection of high-voltage installations using TEA-CO_2 laser-based DIAL. Opt Laser Eng 2010;48:491–9.
[2] Chang L, Jiang YJ. Effect of laser irradiation on $La_{0.67}Ba_{0.33}MnO_3$ thin films. Acta Phys Sin 2009;58:1997–2001.
[3] Hong L, Li L, Ju C. Investigation of cutting of engineering ceramics with Q-switched pulse CO_2 laser. Opt Laser Eng 2002;38:279–89.
[4] Reghu T, Kumar Manoj, Biswas AK, Kukreja LM. A sensitive arc detection technique for reliable operation of high repetition rate TEA CO_2 laser. Opt Laser Technol 2011;43:904–10.
[5] Khumaeni Ali, Niki Hideaki, Fukumoto Ken-ichi, Deguchi Yoji, Kurihara Kazuyoshi, Kagawa Kiichiro, et al. A unique technique of laser-induced breakdown spectroscopy using transversely excited atmospheric CO_2 laser for the sensitive analysis of powder samples. Curr Appl Phys 2011;11:423–7.
[6] Hou JD, Zheng TJ, Lan CZ, Zhou G, Wang DF, Zhao XB. Study on mini high repetition frequency sealed-off TEA CO_2 laser. SPIE 1996;2889:292–7.
[7] Wan CY, Liu SM, Zhou JW, Qi JL. High repetition rate industrial TEA CO_2 laser with average output power of 1.5 kW. SPIE 1995;2502:87–94.
[8] Tian ZS, Wang Q, Wang CH. Investigation of the pulsed heterodyne of an electro-optically Q-switched radio-frequency-excited CO_2 waveguide laser with two channels. Appl Opt 2001;40:3033–7.
[9] Jiang Y, Wang TJ, Gao HZ, Sun H, Kang ZH, Gao JY. Analysis of kinetics of a mechanical Q-switched CO_2 laser with longitudinal DC discharge. J Jilin Univ 2008;46:115–9.
[10] Xie JJ, Guo RH, Li DJ, Zhang CS, Yang GL, Geng YM. Theoretical calculation and experimental study of acousto-optically Q-switched CO_2 laser. Opt Express 2010;18:12371–80.
[11] Smith K, Thomson RM. Computer modeling of gas laser. New York: Plenum Press; 1978.
[12] Soukieh M, Ghani BA, Hammadi M. Mathematical modeling of CO_2 TEA laser. Opt Laser Technol 1998;30:451–7.
[13] Rossmann K, France WL, Rao KN, Nielsen HH. Infrared spectrum and molecular constants of carbon dioxide. J Chem Phys 1956;24:1007–8.
[14] Cheng Cheng, Ma Yangwu, He Sailing. optimization of a sealed-off CO_2 laser resonator by utilizing a genetic algorithm. Opt Laser Technol 2001;33:601–4.