The effects of temporal delay on the performance of an electro-optic Q-switched Nd:YAG laser

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The performances of an electro optic Q-switched Nd:YAG laser at transition line of $^4F_{3/2}\rightarrow{}^4I_{11/2}$ Stark level based on DKDP crystal is presented. The temporal delay time between the ignition of Xenon flashlamp and the Q-switched trigger signal is manipulated to determine the best performances of the Q-switched laser. The results shown that opening the Q-switching is dependent on the pumped energy. The higher the pumping energy the longer the temporal delay is desired to achieve the optimum output. However the temporal delay may remain constant if the laser is pumped with low energy. In general the performance of the Q-switched laser is found independently on the temporal delay, whereby all tested temporal delays almost have similar slope efficiency of 18%.

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1. Introduction

In past few years, laser operating in 1.06 µm had attracted attention due to its wide application in industry. Because of high photon energy, broad absorption bandwidth, easy thermal management etc. 1064 nm Q-switched Nd:YAG laser has a promising potential in the area of electronic devices fabrication, scientific researches and even medical treatment [1]. Specialists all over the world have dealt with high intense Q-switched Nd:YAG in laser therapy [2-4], minor surgery and even tattoo removal [5-7]. In addition, more advantages are offered from 1064 nm laser due to its capability to convert the frequency in second (532 nm), third (266 nm) and fourth (133 nm) harmonic generation. In order to generate so called giant pulse laser, several techniques of light modulation namely electro-optic (EO), acousto-optic (AO), magneto-optic and mechanical switching have been applied widely. Even though AO can produce high repetition rate as EO modulator, but its tendency to turn out long and unstable pulses [8]. Consequentially EO then becomes more priority and preferable one. In addition, EO possess widely used such as in microelectronics, electric appliances and light industry [9]. There are three commonly elements for EO modulator used which are potassium di-deuterium phosphate (KDP or DKDP), lithium niobate ($LiNbO_3$) and β-barium borate (BBO) crystals. BBO has difficulty to grow the crystal in sufficient length along c-axis [10]. $LiNbO_3$ requires only low quarter-wave voltage compared to DKDP crystal and has less thermally induced birefringence feature, but its low optical damage threshold [11-13] and surround with photorefractive effect limits the laser operation. Even though DKDP is a water soluble and hygroscopic type, but its high power density compelling for laser operation in middle and high power as well as preventing the crystal from crack. Thus, DKDP crystal remains the best electro optic modulator in spite of hygroscopic and many difficulties and made most researcher paid attention on it and used simultaneously [13-15].

Compressing into short pulse width and obtaining highest pulse energy are mainly carried out either by an active or passive Q-switched. Zayhowski and Dill [16] reported that a 12 µJ/115 ps at 1 kHz repetition rate and 0.16 µJ/8.8 ns at 2.25 MHz are produced by EO Q-switched $Nd:YVO_4$ diode-end pumped fiber coupled via assistant of etalon. Then, Zajac et al., [17] configured 137 mJ pulsed energy at 91.2 ns pulse width by using EO $LiNbO_3$ crystal for Q-switched Er:YAG flashlamp side-pumped. This is the best achievement worldwide during that time for a mid-infrared Er:YAG Q-switched laser. Few years later Bai et al., [13] attained less than 10 ns with a peak power of 1 MW between the range of 1-20 Hz for Q-switched diode side-pumped Nd:YAG by using DKDP crystal. Later by using double crystal in EO Q-switch modulator, Yu et al., [8] manage to generate 18.4 ns at 11.2 W output power in diode end pumped fiber coupled laser. All of these are reported for an active type of switching. There are few researches have interested on quasi continuous and passive light modulator. For instance, Karlitschek and Hillrichs, [18] obtained a 1.9 mJ/ 13 ns for Nd:YAG and 1.5 mJ/ 9 ns for Nd:KGW in Q-switched diode-pumped passive mode. Then 10 mJ at 20 ns pulse width is gained at quasi continuous active mode by Liu et al., [19]. By using saturable absorber (Cr:YAG), Afzal et al., [20] achieved a 1.5 mJ/ 3.9 ns for linear cavity and 2.1 mJ/ 12 ns for ring cavity experiments. Based on these literatures, mostly interested in improving the pulse width and get better peak power as well as repetition rate. Less attention concerning on the effect of temporal delay upon the laser performances. Adjusting the temporal delay may generate higher output Q-switched pulsed energy rather than relying on the selection of the nonlinear materials. The issue is when the right time to switch off the voltage. Here a delay unit play an important role to control the time between the flashlamp and the Q-switched trigger unit. Prior to switching, it is important to know the life time of Nd ion that is 230 µs. Hence the initial delay between the flashlamp and Q- switched should be greater than 230 µs in order to allow the stimulation emission to occur and consequentially lasing. In commercial laser system normally the delay unit is set at constant value. If the laser system is operated at constant output, the constant delay may not affect the laser performance. However, when dealing with variable outputs, is it the delay time will remain constant? In order to find the answer an experiment was conducted in this work by manipulating the delay unit with respect to the input energy.

In this presence paper the laser performances of an electro-optic Q-switched Nd:YAG laser was studied based on the temporal delay. The output of the laser was measured at various mode including free running, the insertion of nonlinear crystal and Q-switched mode. The laser performance at various delays and input energies were discussed in detail.

2. Theory

In general the performance of laser system can be quantified based on its output-input calibration curve which expressed as [21]:

$$E_{op} = \eta(E_i - E_T) \tag{1}$$

Where E_{op} is energy of output laser, η is slope efficiency, E_i is input energy or pumping energy, and E_T is threshold energy. Once a nonlinear DKDP crystal was interposed into the intra-cavity the insertion loss is estimated as [22]:

$$\delta = 1 - E_2/ E_1 \tag{2}$$

While the percentage rate of the output energy with and without Q-switched is given as:

$$G = E_3/E_2 \times 100\% \tag{3}$$

where E_1 is free running output energy, E_2 is the Pockels cell's output energy (no high voltage applied) and E_3 is Q-switched output energy (with high voltage applied).

3. Experimental section

The layout of a developed Q-switched Nd:YAG laser is depicted in Fig. 1. Electrical and optical components are aligned in this system in order to generate intense laser pulses. A Nd:YAG rod with length of 7 mm and 3 mm diameter (1 at.% Nd^{3+} concentrations) is used to generate transition line of $^4F_{3/2} \rightarrow {}^4I_{11/2}$ Stark level. The cavity is configured based on components that comprised of a rear mirror with 100% high reflectivity at 1064 nm, an output coupler with an optimal transmittance of 50% at 1064 nm, a thin film polarizer and Pockels cell which is a birefringence DKDP crystal. The DKDP is in a cylindrical shape with two electrodes on its surface so as to apply the longitudinal electric field from high voltage power supply driver. The polarizer is set at the Brewster angle. Homemade a fast high voltage switch was developed by previous research [23] was employed to supply into the Pockels cell (PC). The PC driver consists of 15 Zetex avalanche transistors model ZTX415 which all of them connected in series.

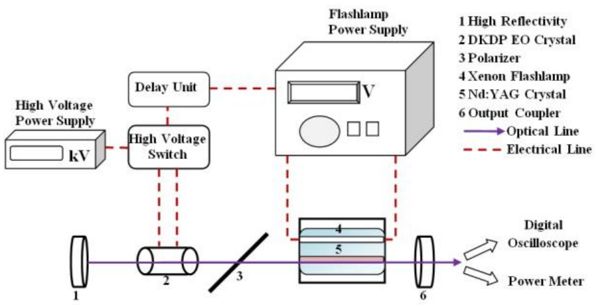

Fig. 1. Schematic diagram of the experimental set up.

The EO q-switched Nd:YAG pulse laser was pumped by a homemade flashlamp power supply [24] while the driver is triggered by simmer mode technique and the repetition rate is fixed at 1Hz. The flashlamp (filled with Xenon gas at 450 torr) and the rod are enclosed in alumina ceramic reflector, cooled by external water circulating at constant room temperature. The pump power is provided by a capacitor charging power supply CCPS, yielding up to 1000V. Variable pump energy in the range between 25–64 J was absorbed along the 7 mm length crystal producing maximum of 60 mJ Q-switched pulsed energy. A tuneable delay unit in the range between 100-500 µs was manipulated to explore the behaviour of DKDP electro optic Q-switched laser. High voltage supplied to DKDP crystal was kept constant at 3.1 kV. The output of Q-switched Nd:YAG laser was measured via broadband Melles Griot power meter and pulse duration was detected by high speed photodetector which cascading the signal into a digital oscilloscope model Tektronix TDS3052 with bandwidth of 500 MHz and sampling rate of 5 G/s. The performance of the DKDP used in our system is estimated by using Eq (2) and (3). The output of the laser was measured in three different mode free running, after the insertion of the DKDP into the cavity with and without voltage applied.

4. Results discussion

The output of EO Q-switched 1064 nm was studied at different time delay between end of pumping pulse (flashlamp) and the opening of the Q-switch (high voltage power supply). In order to obtain highly pulsed energy in short pulse operation, the time triggered is tuning and finally an EO DKDP modulator manages to generate nanoseconds regime pulse for this system. A Q-switched laser around 50 ns was captured such as shown in Fig. 2 with a single pulse 1 Hz repetition rate. A small fluctuations after dropping as depicted in the figure is realized due to the fast changing of the temporal position of the laser pulse. This is in good agreement with the previous result [25]. In addition, it also may be contribution from timing jitter of the photodetector due to the noises that coming from the electronic oscillator, as well as the photocurrent effects.

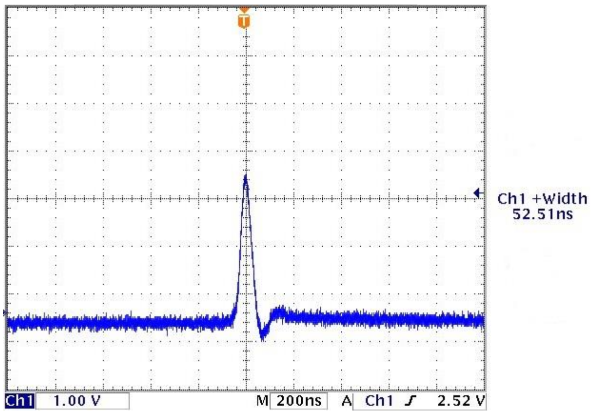

Fig. 2. Pulse shape of the EO Q-switched laser output.

The output of Q-switched Nd:YAG laser was measured with respect to the time delay at different input energy in the range from 25 – 64 J. The experimental results are summarized in Fig. 3. In general all the output of EO Q-switched laser have similar normalized trend. This parabolic trend agree well as reported by Wannop et al., [26] who only work with a constant electrical input energy. However the first four input energy (25 – 45 J) seem to achieve optimum energy at almost the same temporal delay of 240 μs. But as the last three high input energies that are from 50 to 64 J, the profile curve seem to be shifted to the right and each of them are no longer stay at the same temporal delay. The higher the input energy, the longer the temporal delay was realized to achieve the optimum output energy. For example at 56 J input energy the optimum output is achieved at time delay of 260 μs, whereas as the input energy goes to 64 J, the optimum energy is achieved after the delay time was manipulated at 290 μs. Obviously the temporal delay no longer sustain but shifted to 30-60 μs. This indicates that the life time of the Nd ions keep on changing, depending on the pumped energy.

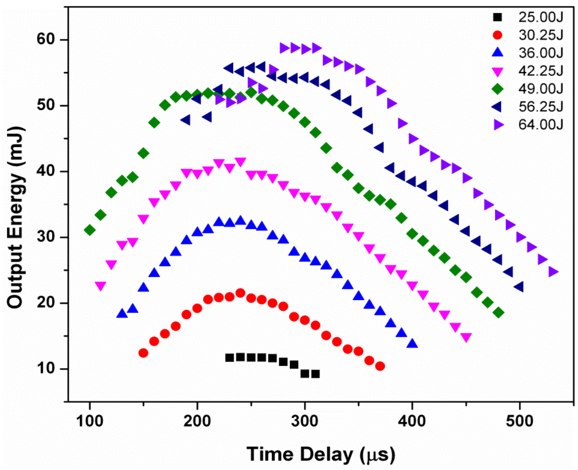

Fig. 3. The output energy of Q-switched Nd:YAG laser as function of time delay.

Further increasing the pump energy deviation of optimal Q-switched output energy, corresponding to the time delays occur. As can be seen from Fig. 3, the laser output energy increases as the value of delay unit increased. Somehow at one point after achieved optimum point it is gradually decreases. From the figure, up to the input of 49 J, the Q-switched pulse energy raise with the increases of the delay unit from 100 – 240 μs respectively. The optimum energy is obtained at corresponding time delay of 250 μs. Beyond that, the output energy decreases correspond to the range of temporal delay between 260-480 μs. The same pattern of incline and decline pulsed energy is observed for the rest of other pumping energies (including 25.00 J, 30.25 J, 36.00 J up to 64.00 J input pump) and this parabolic-trend suits well as reported by Wannop et al., [26] who only concentrated with a constant electrical input energy. In this study as the pumping energy increases, the optimum pulsed energy is shifted to the higher side. The detail results obtained from this study are 25 J/240 μs, 30.25 J/240 μs, 36 J/240 μs, 42.25 J/240 μs, 49 J/250 μs, 56.25 J/260 μs, and 64 J/290 μs.

The effect of higher output laser energy by increasing the pump energy might be due to the more stimulated emission production in the resonator. Actually time delay, t_d should be corresponding to the life time of Nd ion for releasing its access energy from the excited to the lower level energy. If the Q-switch is open after 250 μs pumping with 49 J electrical energy, there are many excited Nd ion are accumulated in the meta-stable state and there are high probability to stimulate by the external photon before manage to spontaneously release the excess energy. Hence giant pulse is produced attributed from accumulation of stimulated emission synchronizelly release, result in high output of laser energy. However if the switch is open too late, like within the temporal delay of 260 < t_d < 480 μs the excess energy is spontaneously release without having a chance to be triggered by the incoming or external photons. If the Q-switch is open within this range of temporal delay, the gain in the resonator is smaller and the output laser energy is also decreased. However within the temporal delay of 100 < t_d < 230 μs after the excited the laser rod, the population inversion does not yet reach it optimum level, thus at that particular moment less occurrence of laser transition hence less stimulated emission to contribute as gain in resonator which result in less output laser energy. The analysis of the laser output energy of this Q-switching as a function of delay time is resourceful for estimating the energy transfer by the excited Nd ions. In other words, the laser transition from upper to lower energy level is somehow either obstructing or controlling by a delay unit system which affecting the stimulated emission processes. High output laser energy obtained due to large contribution from stimulated emission. However this phenomenon is only true for the pumping energy within the range of 25.00 to 42.25 J. As the pumping energy increased more than 45 J, the temporal delay is no longer remained constant, but keep on shifted to a longer one. This means the Q-switching need to open after 260 μs pumping the rod with 56 J, and 290 μs after pumping with 64 J. The higher the pumping energy, the more Nd ions are excited and filled in meta-stable state. However if too much population at the terminal state there is possibilities that other problem will created such as thermal effect. Therefore phonon-ion interactions may involve which resist the release of excess energy process. Thus the higher the input energy, the longer the temporal delay in order to achieve optimum output as shown in Fig. 3.

Fig. 4 shows the performance of Q-switched laser at different delay time. The linear calibration curve indicates that the efficiency of the Q-switched laser is not responsive with the delay in the range of 230 - 310 μs (which is an optimum operation of Q-switched laser output). The optical-electrical conversion efficiency is almost the same ~18% in every optimal delay region. Thus it can be deduced that the efficiency of this EO system is not influence by the variation of time delay, and this in good agreement with theory as shown in Eq. (1). Apart from that, the threshold of all these temporal delay variation is in the range 18 - 21 J. The lowest threshold is at 240 μs (18.28 J) while the highest is at 310 μs (20.78 J). The mechanism for such increases in the threshold with the input energy is still the same as previous discussion is due to the thermal effect.

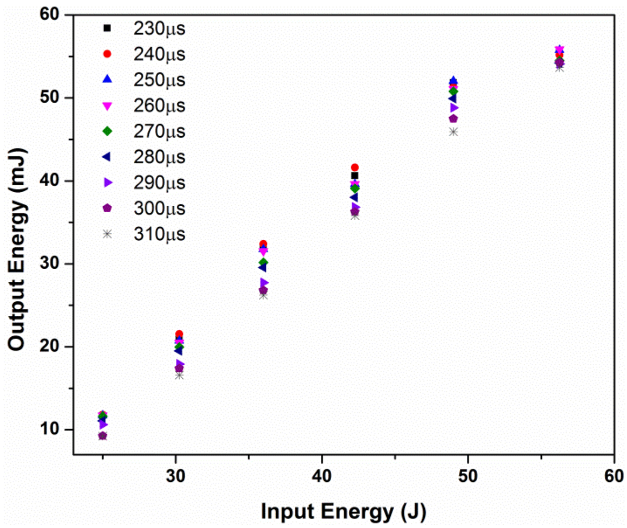

Fig. 4. Optical-electrical conversion efficiency of q-switched Nd:YAG laser at various temporal delay.

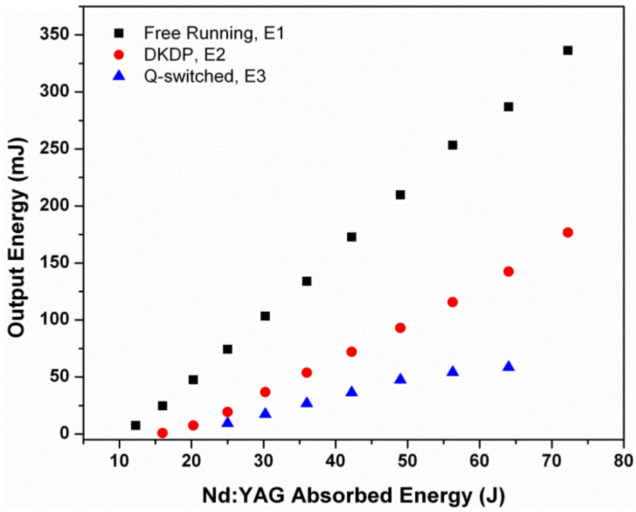

Fig. 5. Performance of the laser at different mode.

Fig. 5 shows the performance of Nd:YAG laser output energy versus absorbed energy in three different conditions that are free running mode E_1, after DKDP is inserted E_2 (without voltage application), and with Q-switched mode E_3. In the figure, it can be inferred that the output energy decreases after the insertion of nonlinear optic material. The laser performances at different mode operations are summarized in Table 1. Obviously the optimum output of the Q-switched laser is almost 5 times smaller than free running system and the threshold for Q-switching is greater than free running with lowest efficiency.

Table 1. Performance of a homemade Nd:YAG laser system.

Operation mode	Threshold, J	Efficiency, %	Optimum Energy, mJ
Free running, E1	11.38	0.55	287.00
After Pockels cell, E_2	18.10	0.31	142.33
Q-switched Mode, E_3	16.18	0.13	58.57

The performance of the laser system and the insertion loss in the cavity were estimated by using Eq. (1) and (2). The result of insertion loss is shown in Fig. 6. Obviously the losses are found exponentially decreasing with the input energy. This indicates that the higher the pumping energy the gain in the resonator is much higher than the losses. In contrast, the delay in opening the switch is required in order to get the optimum output energy. Initially the delay remains constant with relative low pumping energy (25-45 J). However as the pumping energy increased to 50 J, the temporal delay is found drastically increased in order to get the optimum energy. This means the higher the input energy, the longer the temporal delay is required to get optimum delay. Thus as summarization the output Q-switched laser energy is increased with the temporal delay as shown in Fig. 6. This indicates that the higher the pumping energy required a long the time delay to get the optimum output energy. However there are two categories whereby the optimum output laser energy can be described. In the first category, the delay remain constant with input energy that is from 25.00 to 42.25 J, but between 49 to 70 J the time to get the optimum output laser energy is found drastically increase with the input energy.

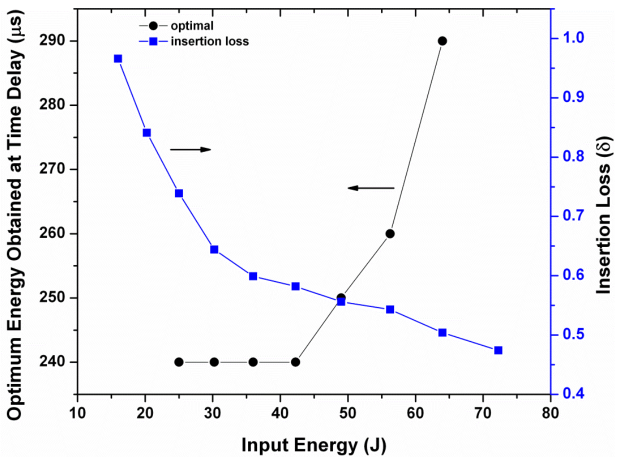

Fig. 6. Optimal energy and insertion loss obtained with respect to the input energy.

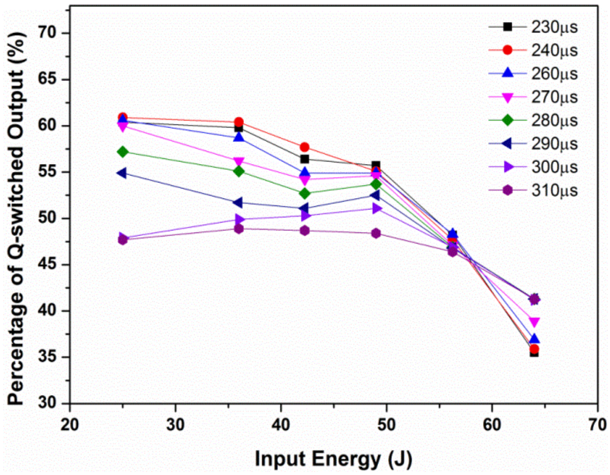

Fig. 7. The percentage rate of Q-switched output, G against input energy at different temporal delay.

The percentage rate of Q-switched output energy (G) is estimated by using Eq (3). The result is presented in Fig. 7. The percentage rate of the Q-switched output energy *G* is found to be nonlinearly decreasing with the input energy. This indicates that the rate of energy loss in Q-switching is decreased appropriate with the insertion loss as depicted previously in Fig. 6. The rate of losses is also getting lower as the temporal delay getting longer. Obviously, the *G* profile at temporal delay of 310 µs is shown as the lowest profile with gradually rate of losses gradient against the input energy. In contrast with the shortest tested temporal delay at 240 µs operation, whereby the *G* profile is the highest and having a rapid rate of losses gradient as the input energy increasing. This means that the rate of losses in Q-switched output energy is high at the short temporal delay and experience drastic change upon pumping energy. Meanwhile only low and almost consistent rate of losses throughout all tested input energy with a longer temporal delay. As a result optimum output is achieved as the Q-switched laser operation at long temporal delay when pumping at high input energy.

5. Conclusions

An electro-optic Q-switched Nd:YAG laser by using DKDP Pockels cell at various temporal delay was demonstrated. The performance of the Q-switched laser was characterized as a function of the temporal delay between the ignition of flashlamp as a pumping source and to cut off the voltage for opening the Q-switched system. The temporal delay is found remain constant at 240 μs after the laser rod was pumped with energy of 25 - 42 J. However the temporal delay of the Q-switched system is rapidly increasing when the pumped energy used in the range of 49 -70 J. The abrupt change indicates that the time for the ion to release the excess energy also change which getting longer than normal Nd:YAG rod. So the life time of Nd:YAG rod is dependent on the pumping energy. The higher the pumping energy the longer the life time for the laser transition to occur thus the longer the time for stimulation emission to take place. Nevertheless, the conversion efficiency of the Q-switched laser system is independent with the temporal delay. This indicates that the performance of laser system is just based on the input-output of the laser. This finding is beneficial for the architect of laser design in order to optimize the laser performance.

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