Different Efficiency Mechanisms Inside Normal Operation, Q-Switched and Amplified Nd: YAG Pulsed Laser

Osama Helal, Liu Ziyu, Tan Yong, Ding Yunfeng, and Hongxing Cai

Abstract—**Till now solid-state lasers still have an expanding phase of applications so there are many endeavors in laser development and optimization to be adaptable for most of these applications. This can be done by understanding well the different mechanisms inside laser system. Different efficiency mechanisms inside normal operation, Q-switched and amplified solid-sate laser are presented in a fruitful way including a thorough description for the mathematical calculation of the efficiency factor and the overall system efficiency for each mode of operation. The calculated efficiencies are verified by an experimental work to withstand on the actual values and verify its correctness with the calculated values. From the experimental work, the output energy and overall system efficiency for normal mode of operation are 128mJ and 1.25% respectively, for Q-switched mode of operation are 110mJ and 1.06% respectively and for amplified mode of operation 282mJ and 2.88% respectively. The energy gain G for the laser amplifier was 2.2.**

Index Terms—**Efficiency factors, laser amplifier, Nd:YAG, -switching, solid-state laser.**

I. Introduction

The first conceptual building block of the laser was Albert Einstein's 1916 proposal that photons can stimulate emission of identical photons from existed atoms [1]. From 1917 until 1960, there are many researches work in the chronology of the birth of the laser, for example, Rudolf Ladenburg reported indirect evidence of stimulated emission in 1928 [2] and Volentin A. Fobrikant suggested that stimulated emission in a gas discharge might amplify light under suitable conditions [3] and so on until Theodore Maiman do the birth of the laser by crossing the threshold of laser age on May 16, 1960 [4]. Soon after Maiman built the first laser, they said laser was "a solution looking for a problem". Laser is not a device invented to fill specific requirements. It was more a discovery than an invention. Laser developers expected that laser is a way for more applications [5]. Solid-sate laser research and development are still in an expanding phase due to its special characteristics [6]. The number of laser applications is increasing in fields like material processing, medicine and biology, measurement techniques and science as well as communication and entertainment beside applications in military weapons and aerospace [7].

In 1961, Hellwarth is the first proposed the Q-switching operation leading to so-called giant laser pulses [8]. In 1964, Joseph E. Geusic, H. W. Macros and LeGrand Van Uitert first demonstrate lasing in Nd-YAG which would become the dominant solid-state laser [9]. As discussed before, solid-state laser is an expanding phase and there are still incomplete topics that may play an important role in future research and development of solid-state lasers. For example, the "green gap" between 535 and 460 nm that cannot be covered by semiconductor lasers yet [7], mode-locked thin disk lasers as they delivered the highest average output power and pulse energies that can be obtained directly from mode-locked oscillators [10], the highest cw solid-state laser output power of 100KW obtained by coherent beam combined of several 15KW of class modules was realized recently with Nd:YAG [11], the progress in fabrication of ceramic gain materials which add a new degree of freedom to create the perfect gain medium and so on [7].

According to these open incomplete area of applications, the present work introduce a thorough study for normal mode, Q-switched and amplified pulsed solid-state laser. The three modes of operations are studied from the point of view of efficiency factors for different mechanisms inside each mode of operation. In section 2, the theories and equations describing different mechanisms inside the three modes and how deal with them is introduced in a fruitful way. A calculation of these efficiency factors inside each mode of operation is presented in section 3 arithmetically. Section 4 provides the experimental part of this work for each mode which is done on a Nd:YAG laser as a type of solid-state laser. An analysis between the values of the efficiency factor and the overall system efficiency which obtained from calculation and experiment will be done.

II. Theoretical Part

A. Normal Mode of Operation Useclaser

The energy transfer mechanisms which are responsible for the conversion process of the electrical energy input to the flashlamp to the laser energy output from the resonator are:

1) *Pumping efficiency* η_P which represents the fraction of the electrical input power that is emitted as optical radiation within the absorption region of the gain medium.
2) *Transfer efficiency* η_t

$$\eta_t = \eta_{t_g} x \eta_{t_o} \tag{1}$$

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$$\eta_{t_g} = (1/\pi)[\alpha_P + (r_R/r_L)(\theta_P - \theta)] \quad (2)$$

$$\eta_{t_o} = R_W\ (1 - R_r)(1-\delta)(1 - A_n/A_{tot.}) \quad (3)$$

where η_{t_g} is the fraction of rays leaving the source and intersecting the laser rod, η_{t_o} is the optical efficiency of the cavity which essentially includes all the losses inside the cavity, $\alpha_P = cos^{-1}\{(1/e)[1-((1-e^2)/2)(1+r_R/r_L)]\}$, $\theta_P = sin^{-1}[(r_L/r_R) sin\alpha_P]$, $\theta_1 = sin^{-1}(r_L/4ae)$, e is the eccentricity (c/a), R_W is the reflectivity of the cavity walls at the pump bands, R_r is the fraction reflected at the laser rod surface and glass envelope of the cooling jackets, δ is the optical resonator loss and $A_n/A_{tot.}$ is the ratio of the nonreflecting area of the cavity A_n to the total inside area $A_{tot.}$ [12].

3) *Absorption efficiency* η_a which represents the fraction of the absorbed pump radiation into the pump bands of the gain medium.

$$\eta_a = 2\alpha_o r_R\ exp(-\alpha_o r_R) \quad (4)$$

where α_o is the average absorption coefficient over the spectral emission range of the lamp.

4) *Quantum efficiency* η_Q which represents the number of the photons contributing to laser emission divided by the number of pump bands photons.
5) *Quantum defect efficiency* η_S is the fraction of the stored energy that remains available at the time of the emission of the laser pulse.

$$\eta_S = h\nu_L/h\nu_P = \lambda_P/\lambda_L \quad (5)$$

6) *Overlap* efficiency η_B which is the ratio between resonator mode volume and pumped volume of the active material.
7) *Coupling efficiency* η_C represents the reduction of the available output power due to the losses inside the resonator.

$$\eta_C = (-lnR)/(-lnR + \delta) \quad (6)$$

where R is the reflectivity of the output mirror.

Both the efficiency factor η which contains all the efficiency factors of the conversion process before laser extracted from the resonator and the system efficiency $\eta_{sys.}$ can be calculated from equations (7) and (8) respectively.

$$\eta = \eta_P \eta_t \eta_a \eta_Q \eta_S \eta_B \quad (7)$$

$$\eta_{sys.} = \eta\,\eta_C \quad (8)$$

The optimum mirror reflectivity $R_{opt.}$ for maximum output energy from the resonator is:

$$-\ln R_{opt.} = \left(\sqrt{(2g_o\, l_R)/\delta} - 1\right)\delta \quad (9)$$

$$2g_o\, l = (2\sigma\tau_f\,\eta P_{in})/(h\nu_L A) \quad (10)$$

where g_o is the gain coefficient inside active material, l_R is the active material length, σ is the stimulated emission cross-section and τ_f is the fluorescence lifetime.

B. Q-Switched Mode of Operation Nseclaser

The energy transfer mechanisms which responsible for the conversion process of the electrical input energy to laser output is the same as for the normal mode of operation except that the coupling efficiency η_C is replaced by the extraction efficiency η_E. For Q-switching operation:

$$\eta_{sys.} = \eta_P\ \eta_t\ \eta_a\ \eta_Q\ \eta_S\ \eta_B\ \eta_E \quad (11)$$

$$\eta_E = \eta_{EQ}\eta_{ASE}\eta_{ST} \quad (12)$$

$$\eta_{ST} = (\tau_f/t_P)[1 - exp(-t_P/\tau_f)] \quad (13)$$

$$\eta_{EQ} = 1 - (1 + ln\, Z/Z) \quad (14)$$

$$Z = (2g_o l/\delta) \quad (15)$$

where η_{ST} and η_{ASE} are the losses prior to opening of the Q-switch. They are referring to the fluorescence losses and ASE losses (Amplified Spontaneous Emission) respectively, η_{EQ} is the extraction efficiency of the Q-switch process and Z is a single dimensionless parameter.

The output energy E_{out} and the expected pulse width t_P from the laser can be obtained through equations (16) and (18) respectively.

$$E_{out} = E_{sc}(Z - 1 - ln\, Z) \quad (16)$$

$$E_{sc} = (Ah\nu\delta)/(2\sigma) \quad (17)$$

$$t_P = (t_r/\delta)\{(ln\, Z)/(Z[1 - a(1 - ln\, a)])\} \quad (18)$$

where E_{sc} is a scalar factor with the dimension of energy, t_r is the transit round-trip time in the resonator $(t_r = 2l/c)$ and $[a = (Z-1)/(Z\, lnZ)]$. Both E_{out} and t_P are calculated for optimum mirror reflectivity $R_{opt.}$, equation (19), that achieves maximum output energy from the resonator and the calculated values of E_{out} and t_P may not be comparable with the experimental data if the system did not operated with $R_{opt.}$.

$$R_{opt.} = exp\{-\delta[(Z - 1 - ln\, Z)/(ln\, Z)]\} \quad (19)$$

C. One-Pass One-Head Amplified Mode of Operation

The generation of an amplified pulse is based on the combination of a master oscillator and a power amplifier. Equation (20) represents the amplifier gain G.

$$G = (E_s/E'_{in})\, ln\left[1 + \left(exp\left(E'_{in}/E_s\right) - 1\right)G_o\right] \quad (20)$$

where E_s is the saturation fluence parameter $(E_s = h\nu/\sigma)$, E'_{in} is the amplifier signal input fluence and G_o is the small-signal, single-pass gain $[G_o = exp(g_o l)]$. The amplifier signal output fluence E'_{out} and the extraction efficiency η_E can be calculated from equations (21) and (22) respectively. Equation (11) gives the overall system efficiency $\eta_{sys.}$.

$$E'_{out} = GE'_{in} \quad (21)$$

$$\eta_E = \left(E'_{out} - E'_{in}\right) / \left(g_o l E_s\right) \tag{22}$$

III. Calculation Part

A. Normal Mode of Operation Useclaser

The efficiency factor and the system efficiency can be obtained by calculating the different efficiency factors inside the system. Now, a calculation of each process will be done. There are some processes that cannot be calculated, the factors of these processes will be assumed based on references for similar systems but the way to obtain those assumed efficiencies accurately is listed.

The pump efficiency η_P, in present calculation, will be assumed to be 0.54 [13], for exact value, it can be obtained by recording the fluorescence of the xenon lamp and using a software to get the exact optical energy output from the lamp. The transfer efficiency η_t can be calculated by multiplying the capture efficiency η_{t_g} and the transmission efficiency η_{t_o}, equation (1). The former will be 0.79161 from equation (2) for the pump cavity dimensions $2a = 35\ mm$, $2b = 32\ mm$ and $2c = 14\ mm$ and the later will be 0.58551 from equation (3) with $R_W = 0.85$ [14], $R_r = 0.0848$ [15], $\delta = 0.243$ [16] and $A_n/A_{tot.} = 0.005732$. Then η_t will be 0.46350. The absorption efficiency η_a is calculated from equation (4) to be equal to 0.13054 for average absorption coefficient $\alpha_{o_{av.}}$ equals to $0.28\ cm^{-1}$. The quantum efficiency η_Q will be assumed to be 0.8 [17, 18]. From equation (5), the quantum defect efficiency η_S is equal to 0.75188 and the overlap efficiency η_B is assumed to be 0.85 [19]. η_B can be calculated exactly if the gain and the beam profiles are known. These distributions of the beam profiles can be obtained from images taken with CCD camera which will record the profiles of the fluorescence and laser beam output. With the radial spot sizes of the Gaussian approximations obtained and from $\eta_B = \left(2\omega_m^2\right)/\left(\omega_p^2 + \omega_m^2\right)$, the accurate value of η_B can be obtained.

The efficiency factor η is the product of all calculated efficiencies above, equation (7), and it will be equal to $0.0167 = 1.67\,\%$. Calculation of the overall system efficiency $\eta_{sys.}$ needs the coupling efficiency η_C to be calculated. Equation (6) gives η_C equal to 0.4787 for the output mirror reflectivity $80\,\%$. Then the system slope efficiency $\eta_{sys.}$ will be $0.008 = 0.8\,\%$ and the corresponding output energy E_{out} from the system will be $158.69\ mJ$.

The calculation will be proceeded to get the output mirror reflectivity $R_{opt.}$ which achieves the maximum output energy from the optical resonator and the corresponding output energy when the output mirror is $R_{opt.}$. The optimum mirror reflectivity $R_{opt.}$ will be $0.36409 = 36.409\,\%$. It is calculated from equation (9) with the aid of equation (10) and with $\sigma = 2.8 x 10^{-19} cm^2$, $\tau_f = 230\ \mu sec$, $h\nu_L = 186.8233 x 10^{-21}\ J$ and $P_{in} = 110.25\ KW$ for flashlamp pulse width $t_P = 180\ \mu sec$. The corresponding η_C, $\eta_{sys.}$ and E_{out} for $\left(R = R_{opt.} = 36.409\,\%\right)$ will be 0.80612, $1.346\,\%$ and $267.16\ mJ$ respectively.

B. Q-Switched Mode of Operation Nseclaser

There is no change in the value of the efficiency factor η between normal mode of operation and the Q-switched mode of operation. The overall system efficiency $\eta_{sys.}$, equation (11), depends on the extraction efficiency η_E which in turn depends on η_{ST}, η_{ASE} and η_{EQ}, equation (12). Laser design trade-offs and performance projections and system optimization can be accomplished quickly with the help of η_{EQ} only as η_{ST} and η_{ASE} are almost equal to one for Q-switched operation $\left(\eta_E \cong \eta_{EQ}\right)$ [18]. At the end of the calculations of the Q-switched pulsed solid-state laser, a check for η_{ST} will be done to ensure that it has the value of one for Q-switched operation.

A Q-switched laser is a type of a pulsed laser which shortens its output pulse width, boosts peak output power and improves the consistency of the output from pulse to pulse. However, these will likely be a reduction in the total energy in the output when a laser is operated in Q-switched mode. The Q-switched to normal mode energy extraction efficiency is between $80 \sim 90\,\%$ from laboratory work. So the expected Q-switched laser system efficiency $\eta_{sys.}$ on the average will be $0.68\,\%$ and the corresponding expected output energy E_{out} will be $134.95\ mJ$. From equation (17), the scalar factor E_{sc} can be calculated to be $15.9177\ mJ$. So to achieve the expected output energy $134.95\ mJ$, the ratio E_{out}/E_{sc} is equal to 8.478. From equation (16), the value of Z can be obtained to be 11.95951 and the single pass power gain of the rod G_o will be 4.27627, equation (15). The extraction efficiency η_{EQ} of the Q-switched process can be calculated from equation (14) to be 0.70889 which in turn is the extraction efficiency η_E for Q-switched operation. Then the system efficiency $\eta_{sys.}$ will be $0.01184 = 1.184\,\%$, from equation (11). The value of $\eta_{sys.}$ is different from the value calculated before $\left(\eta_{sys.} = 0.68\,\%\right)$. That is because, the later value is calculated for the optimum mirror reflectivity $R_{opt.}$ which achieves maximum output energy from the resonator while the former is calculated for the output mirror reflectivity $80\,\%$. Again as done for the normal mode of operation, the calculation will be proceeded to get the optimum mirror reflectivity $R_{opt.}$ for the Q-switch operation. $R_{opt.}$ can be calculated from equation (19) to be $0.43596 = 43.96\,\%$. If the system is operated in the normal mode of operation with output mirror reflectivity equal to the optimum mirror reflectivity $43.96\,\%$, the coupling efficiency η_C, the overall system efficiency $\eta_{sys.}$ and the output energy E_{out} will be 0.77358, $0.01292 = 1.292\,\%$ and $256.37\ mJ$ respectively. Hereby the expected system efficiency $\eta_{sys.}$ for the Q-switched operation will be $1.098\,\%$ $\left(0.01292 x 85\% = 0.01098\right)$ which is the same as calculated before which was $1.184\,\%$.

The expected pulse width t_P for the giant pulse produced from the Q-switched operation will be calculated from equation (18) to be $t_P = 9.39227\,nsec$ as $t_r = 4.41333\,nsec$ and $a = 0.32592$.The output energy E_{out} is $260.17\ mJ$ and the peak power is $27.70044\,MW$.

Before finish the calculations of the Q-switched operation, a check for the value of η_{ST} to be equal one will be done. From equation (13), η_{ST} can be calculated to be $0.99998 \approx 1$ $(check\ success)$.

C. One-Pass One-Head Amplified Mode of Operation

The amplifier head has the same geometry and specifications as the oscillator head. They are typical, except that the electrical energy input to the lamp for the amplifier is smaller than the oscillator.

The small-signal, single-pass gain G_o inside amplifier can be calculated from $[G_o = exp(g_o l)]$ with the aid of equation (10) and it is found to be 3.68047 and the saturation fluence E_s is equal to $667.23\ mJ/cm^2$. The amplifier input energy is the output energy from the oscillator which is $158.69\ mJ$. The amplifier signal input fluence $E_{in}^{'}$ will be $808.19964\,mJ/cm^2$. Then from equation (20), the energy gain G for a laser beam passing through the laser amplifier is 1.87391 and, from equation (21), the amplifier signal output energy $E_{out}^{'}$ is $1.51449\,J/cm^2$. The extraction efficiency η_E will be 0.81236 from equation (22) and the overall system efficiency of the amplifier, from equation (11), will be $0.01357 = 1.357\,\%$.

Also in laser amplifier mode, the extraction efficiency η_E can be also calculated from equation (12) as the Q-switched mode. Then from this equation with the help of equation (13) which gives η_{ST} to be 0.69356, η_{ASE} can be calculated which in turn must be equal to one according to the substitution in equation (12).

IV. The Experimental Work

Fig. 1. is schematic diagram of the system setup including the three modes of operation; normal, Q-switched and amplified mode of operation. The laser head of the master oscillator is the same as that of the amplifier. Each laser head is a single elliptical pump cavity having a laser rod $101\ mm$ in length and $5\ mm$ in diameter and a Xenon flashlamp $90\ mm$ arc length and $4\ mm$ bore diameter. The Xenon lamp has an impedance parameter $28.8\ \Omega.A^{1/2}$. The dimensions of the pump cavity are $2a = 35\ mm$, $2b = 32\ mm$ and $2c = 14\ mm$. The pump cavity is aluminum polished on its inner walls. The laser head of the master oscillator is surrounded by two mirrors. One of them is the rear mirror and it is a Plano-concave mirror with diameter one inch and radius of curvature of $3\ m$. The other mirror is the output mirror. It is a flat mirror with radius one inch and has a reflectivity of 80% at the laser wavelength $1064\,nm$. The two inclined mirrors in the right hand side of the Fig. 1. are for guiding the laser beam from the master oscillator to the amplifier in the case of the amplified mode of operation.

A. Normal mode of operation $(\mu sec\ laser)$

The laser output energy from the simple solid-state Nd:YAG laser system and the electrical input energy to the Xenon flashlamp are recorded in Table I and the corresponding system efficiency of each input energy.
From the experimental data, the output laser energy E_{out} and the corresponding system efficiency $\eta_{sys.}$ for the electrical input energy $E_{in} = 19.845\ J$ are $128\ mJ$ and 0.64484% respectively. Before, both E_{out} and $\eta_{sys.}$ are calculated arithmetically and were found to be $156.65\ mJ$ and $0.8\ \%$. Both system efficiencies measured and calculated are not completely comparable because the absorption efficiency η_a is calculated for the average absorption coefficient $0.28\ cm^{-1}$. $\alpha_{o_{av.}}$ may be varied according to the doping of the *Nd* atoms and the temperature gradient technology growth of the crystal [20]. A small change in the temperature leads to a change in $\alpha_{o_{av.}}$. Fig. 2. is the measured output energy versus input energy. From this curve, the slope which represent the overall system efficiency is $\eta_{sys.} = 0.012538$ and the threshold input energy is $E_{in_{th.}} = 9.43951\,J$.

B. Q-switched mode of operation

The same as before but with the Q-switch crystal powered on, the laser output energy and the electrical input energy are recorded in table (2) and the corresponding system efficiency $\eta_{sys.}$ and pulse width t_P .

From the experimental data, the output laser energy E_{out} and the corresponding system efficiency $\eta_{sys.}$ for the electrical energy input $E_{in} = 19.845\ J$ are $110\ mJ$ and 0.55416% respectively. By comparing both the measured and the calculated values of E_{out} and $\eta_{sys.}$ for optimum mirror reflectivity $R_{opt.}$, it were found that they are comparable. Fig. 3. represents the measured output energy versus input energy. From Fig. 3. the slope efficiency is $\eta_{sys.} = 0.01058$ and the threshold input energy is $E_{in_{Th.}} = 9.6419\,J$.

C. Amplified mode of operation

The output laser beam from the normal mode of operation is allowed to pass through one head of Nd:YAG amplifier for one pass. The output from laser amplifier is recorded in table (3) for each input pulse from the Nd:YAG master oscillator.

From the table, the expected amplified pulse from the amplifier is $282\,mJ$ for the $128\,mJ$ input energy from the master oscillator which corresponding to $19.845\,J$ electrical input energy to the flashlamp of the master oscillator.

The energy gain G for a light beam passing through the laser amplifier will be around 2.2 . Comparing both measured and calculated values of the energy gain G and the amplifier signal output energy E_{out}, they are almost comparable. The former was $G = 2.2$ and $E_{out} = 282\,mJ$ respectively and the later was $G = 1.87391$ and $E_{out} = 297.37078\,mJ$ respectively.

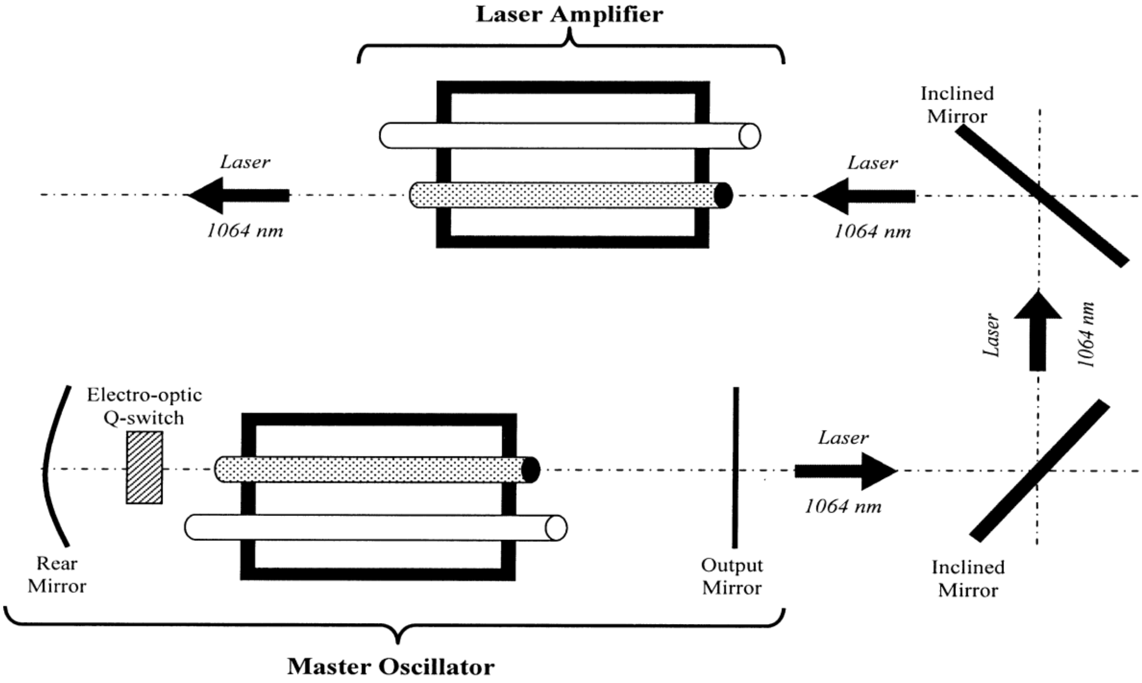

Fig. 1. System setup.

TABLE I: INPUT ENERGY VS. OUTPUT ENERGY FOR NORMAL MODE

Input Voltage $V\ (V)$	Input Energy $E_{in}\ (J)$	Output Energy $E_{out}\ (mJ)$	Efficiency $\eta_{sys.}\ (\%)$
480	11.52	25	0. 21701
510	13.00	46	0.35385
540	14.58	61	0.41838
570	16.25	89	0.54769
600	18.00	109	0.60556
630	19.85	128	0.64484

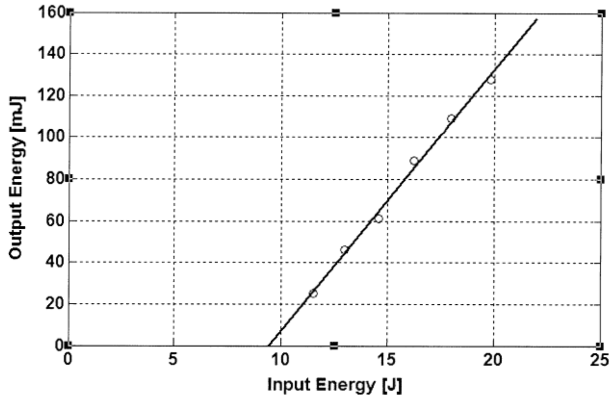

Fig. 2. Output vs. input energy for normal mode.

TABLE II: INPUT ENERGY VS. OUTPUT ENERGY FOR Q-SWITCHED MODE

Input Voltage $V\ (V)$	Input Energy $E_{in}\ (J)$	Output Energy $E_{out}\ (mJ)$	Pulse Width $t_P\ (n\,sec)$	Efficiency $\eta_{sys.}\ (\%)$
480	11.52	23	16	0.19965
510	13.00	37	14	0.28462
540	14.58	48	14	0.32922
570	16.25	66	12	0.40615
600	18.00	91	12	0.50556
630	19.85	110	12	0.55416

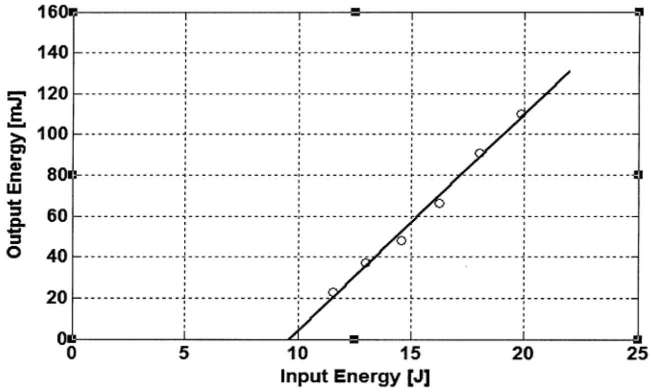

Fig. 3. Output vs. input energy for Q-switched mode.

TABLE III: INPUT ENERGY FROM MASTER OSCILLATOR VS. OUTPUT ENERGY

Input Energy $E_{in}\ (mJ)$	Output Energy $E_{out}\ (mJ)$	Gain G
11.52	23	1.7200
13.00	37	1.5435
14.58	48	1.8689
16.25	66	1.7753
18.00	91	1.9817
19.85	110	2.2031

TABLE IV: ELECTRICAL INPUT ENERGY FROM FLASHLAMP VS. OUTPUT ENERGY

Input Voltage $V\ (V)$	Input Energy $E_{in}\ (J)$	Output Energy $E_{out}\ (mJ)$	Efficiency $\eta_{sys.}\ (\%)$
480	11.52	43	0.37326
510	13.00	71	0.54615
540	14.58	114	0.78189
570	16.25	158	0.97231
600	18.00	216	1.2
630	19.85	282	1.4207

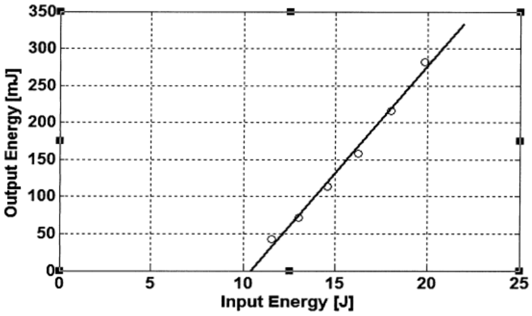

Fig. 4. Output vs. input energy for amplified mode.

The electrical input energy to the lamp versus the laser pulse output from the amplifier are recorded in Table IV. The measured system efficiency of the amplifier for the output amplified energy $E_{out} = 282\,mJ$ is $\eta_{sys.} = 1.4207\%$, and it is accepted. Fig. 4. is the output versus input energy for amplified mode of operation at which the slope efficiency $\eta_{sys.}$ and the threshold input energy $E_{in_{Th.}}$ are 0.028814 and $10.409\,J$ respectively.

V. Discussion and Conclusion

Three modes of operation of a Nd:YAG pulsed laser were listed; normal, Q-switched and amplified mode. The different efficiency factors controlling the different mechanisms inside each mode were presented. How to obtain the efficiency factor and the overall system efficiency for each mode was done arithmetically and experimentally. In the calculation part of the Q-switched mode, it were seen that the overall system efficiency is different between calculation and experiment and this was because the calculation part was done on the optimum reflectivity of the output mirror which achieved the maximum output energy from the system but the experimental part was done on the output mirror reflectivity 80% which was far different from optimum mirror reflectivity. Also in the calculation part, it could be seen how the efficiency factor was the same for the three modes but the difference was in the overall system efficiency which was controlled in a different way in each mode according to coupling efficiency in normal mode and extraction efficiency in Q-switched and amplified modes. The calculation part was supported by an experimental part to withstand on the exact efficiencies for each mode and confirm the accuracy of the calculation part.

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