One stage Nd-glass Oscillator – amplifier ,Design Aspects

M.S.Mehdi (Ph.D.), F.F.Rasheed (Ph.D.),K.A.Hubaiter(M.Sc)

Abstract:

This work deals with the design and construction of Nd:glass oscillator and one stage amplifier system. Parameters, which effect the system operation like mode of operation are studied in free running mode, this operation help to obtain wide pulse duration of the output laser pulse.

The output energy from the oscillator found to be (565 mJ) with pulse duration of (80us). The slope efficiency of the oscillator was (0.71%) and (0.606%) overall efficiency.

The output energy from the amplifier was ~ 900mJ and the overall efficiency of the oscillator – amplifier equal to (1.18%), amplification ratio of (1.6).

A good agreement between the theoretical and experimental results was achieved for both oscillator and amplifier outputs. The stability of the of the system was studied during the operation when the input energy was fixed at suitable value.

الخلاصة:

يتضمن البحث دراسة تصميم وبناء منظومة مذبذب – مكبر بمرحلة واحدة لليزر N d:glass. تمت دراسة العوامل المؤثرة على تشغيل المنظومة مثل نمط الإشتغال حيث تم العمل في هذا البحث في نمط التشغيل الحر للحصول على أمد نبضة كبيرة نسبياً للخرج الليزري.

إن طاقة النبضة التي تم الحصول عليها من منظومة المذبذب وحدها بحدود 565 mJ وبعرض نبضة مقدارها (FWHM=80 us) . تم حساب كفاءة الميل للمنظومة بعد حساب طاقة العتبة والتي كانت بحدود 0.71% والكفاءة الكلية لمنظومة المذبذب مع الخسارة كانت بحدود 0.606 %.

إن مقدار الطاقة الخارجة من المكبر كانت بحدود 900 mJ والكفاءة الكلية لمنظومة مذبذب – مكبر كانت بحدود 1.18% . أما نسبة التضخيم للنبضة الداخلة كانت بحدود 1.6 .

لقد تم الحصول على توافق جيد نوعاً ما للحسابات النظرية والعملية لطاقة الخرج الليزري لكـــل مـــن المذبذب والمكبر . وكذلك تمت دراسة إستقرارية المنظومة أثناء الأداء ولعدة نبضات عند ثبوت الطاقـــة الداخلـــة .

Introduction:

The first demonstration of laser action in Nd-doped glass by snitzer was in 1961[1]. Solid state host material may be broadly grouped into crystalline solids and glasses. The host must have good optical, mechanical and thermal properties for severe operating condition of practical laser.

Material for laser operation must posses sharp fluorescent lines, strong absorption bands, these characteristics are generally shown by solids (crystal or glass), which incorporate in small amounts elements in which optical transitions can occur between state of incomplete element shells.

The energy buildup in a laser pulse propagating through a laser amplifier has been studied by a number of works in the field. Petars et al [2] investigated the exponential amplification of a "non – Q – switched " laser pulse through an amplifier, Geusic reported experiments in laser pulse amplification by amplifier rods driven by both non–Q–switched and Q – switched oscillators. But again all of these experiments considered only the exponential amplification regime. Frontz& Nodvik [3] and others theoretically considered the pulse propagation problem through a ruby amplifier by solving the time – dependent photon transport equation for varions types of input pulse shapes.

Steele & Davis [4] reported a set of experiments where the amplifier gain was measured, their experiments performed in a low energy regime. Davis & Sooy [5] solved a set of amplifier equations with and without regeneration, and their solutions covered energy ranges from small signal gain to saturation.

The possibility of light pulse amplification in a laser amplifier was first demonstrated by Arcchi & Schulz [6] thus the generation of high – power light, pulses is based on the combination of master oscillator and multistage amplifier.

In (1996) M.R.Ismaeel [7] obtained (140 mJ) from two stages Nd:YAG amplifier. With rod dimensions (5cm) length and diameter (0.4cm).

In (1999) N.N.Nassir [8] obtained a Q-switched Nd:YAG oscillator (136mJ) output energy with (35ns) pulse duration, pumping one – stage Nd:YAG amplifier with the same dimension of the rod used by Ismaeel [7], giving an output energy (318mJ) with total efficiency of osc- amp 0.35%. In our work we used Nd: glass rod (7.5cm) length and (0.6cm) diameter as an oscillator and one stage Nd:glass amplifier with the same dimensions.

The output energy of the oscillator and the slope efficiency:

B.A.SEE [9] derived an expression for the output energy from pulse pumped laser was

$$E_{osc} = I_{sat}\tau_f A\eta(r-1) \qquad \ldots(1)$$

Where: I_{sat} :is the saturation intensity

τ_f : the fluorescent decay time

A: is the rod area

η : Energy coupling term

r: Inversion ratio

The coupling term η equal to [10]

$$\eta = \frac{2(1 - R_1)}{R_1^{1/2}\left(-\ln\left(T_f^2 R_1\right)\right)} \qquad \text{... (2)}$$

Where: R_1 :Reflectivity of output

T_f : total transmission of the laser cavity

Koechner [1] considered :

$-\ln(T_f)^2 = L$ L: Optical loss

Therefore we can rewrite eq. (2) into :

$$\eta = \frac{2(1 - R_1)}{R_1^{1/2}(L - \ln R_1)} \qquad \text{...(3)}$$

When the lamp input energy E_{th} for threshold operation has been replaced by E_{in}, the input energy above threshold equals:

$$E_{out} = \sigma_s\left(E_{in} - E_{th}\right) \qquad \text{...(4)}$$

E_{th}: the lamp – input energy required achieving threshold from the following equ. :

$$E_{th} = (L - \ln R_1) \backslash 2k \qquad \text{...(5)}$$

σ_s : Slope efficiency of the laser output varies lamp-input curve.

K: Pumping factor.

Therefore :

$$\sigma_s = K I_{sat} A \eta \qquad \text{...(6)}$$

Hence, the slope efficiency is simply the product of all the individual efficiencies of the system, the output coupling efficiency (η) can be optimized by proper selection of the output mirror reflectivity.

Laser Amplifier:

In an oscillator-amplifier system, the pulse width beam divergence & the spectral width are primarily determined by the oscillator [10] where as pulse energy & power are determined by the amplifier, therefore from an oscillator-amplifier combination one can obtain either a higher energy than can be achieved from the oscillator alone, also to increase the brightness of the output beam.

In the design of a laser amplifier, the following aspects must be considered:

1. Gain and energy extraction.
2. Wave front and pulse shape.
3. Energy and power densities at the optical elements of the amplifier system.
4. Feedback in the amplifier, which may lead to superradiance or Prelasing of primary interest in the design of amplifier, is the gain, which can be achieved, and the energy, which can be extracted from the amplifier.

The rod length in an amplifier is determined primarily by the desired gain.

There are two regimes of light amplification. Short pulse and steady state or long pulse.

We will see, however, that in the case of pulses, which are short compared to the fluorescent lifetime of the material, the amplification depends on the energy density, whereas in the case of long pulses or CW mode of operation the gain depends on power density [11].

Pulse Amplification:

The amplification process is based on the energy stored in the upper laser prior to the arrival of the input signal. As the input pulses passes through the rod, the atoms are stimulated to release the store energy.

If we take for the input to the amplifier a square pulse duration (t_p), and initial photon density, therefore the input energy per unit area can be expressed as:

$$E_{in} = C\phi_o t_p h\upsilon \qquad \ldots(7)$$

C: Light velocity

A saturation fluence E_s can be defined by

$$E_s = \frac{h\upsilon}{\gamma\sigma} = \frac{E_{st}}{\gamma g_o} \qquad \ldots(8)$$

σ : Absorption cross-section.

g_o : small-signal gain coefficient.

$\gamma = 1 - g_2/g_1$ is the degeneracy parameter .

In a four level system γ=1, and the total stored energy per unit volume in the amplifier is:

$$E_{st} = g_o E_s \qquad \ldots(9)$$

The gain of the amplifier

$$G = \frac{E_s}{E_{in}} \ln\left\{1 + \left[\exp\left(\frac{E_{in}}{E_s}\right) - 1\right] G_o\right\} \qquad \ldots(10)$$

G_o :small – signal single pass gain

$$G_o = \exp(g_o l) \qquad \ldots(11)$$

For a low input signal E_{in} such that $E_{in}/E_s \ll 1$

Then eq.(10) becomes

$G \sim G_o = \exp(g_o l)$

Equation (10) can be recast into a form, which makes it convenient to model the energy output and extraction efficiency for single and multiple stage.

If (E_i) is the input energy to the amplifier and (E_0) is the output from the amplifier therefore [10]:

$$E_o = E_s \ln\left\{1 + \left[\exp\left(\frac{E_i}{E_s}\right) - 1\right]\exp(g_o l)\right\} \qquad \ldots(12)$$

And the extraction efficiency

$$\eta_E = \frac{E_o - E_i}{g_o l E_s} \qquad \ldots(13)$$

Experimental part:

1. Design and construction of power supply.

A (2KV) D.C power supply (0.5 Amp) was designed and shown in fig (1) because of the limitation of the flash lamp characteristics (maximum operating voltage 2KV).

The output voltage of power supply is connected to two charging circuits (pulse forming network PFN) in parallel, one for the oscillator and the second for the amplifier.

1-1 Pulse forming network

The PFN used is a single - mesh (LC) network with C = 50 μF and L= 20 μH , the network stores the discharge energy and delivers it to the flash lamp in the desired current pulse shape .

1-2 Triggering circuit:

The two most common methods of triggering flash lamps are external and internal triggering. In our work external triggering was used because cooling technique was not used.

The trigger circuit consists of two main parts, the first one is used to rise the voltage between (20 - 30 kv) using trigger transformer (1: 100), the second circuit is used to control the process of the thyristor ON/ OFF as shown in Fig (2).

The function of the trigger signal is to create an ionized spark streamer between the two electrodes so that the main discharge can occur.

In external trigger device a wire is wrapped a round the flash lamp between the electrodes and connected to the secondary of the trigger transformer, a high voltage is generated by discharging a capacitor through the primary of the transformer. The switching element was a thyristor (type BTX, 8A, 400V).

2. Design of the optical resonator:

The optical resonator of the oscillator consists of four main parts as shown in Fig (3).

2-1 Optical resonator:

A plane - parallel optical resonator was used with two mirrors the rare mirror of reflectivity ($R_2 = 100\%$ for $\lambda = 1.06\ \mu m$), and the output coupler with partial reflectivity($R_1 = 65\%$) for the same wavelength . The two mirror were fixed outside the laser cavity with a distance (L = 18 cm) between them.

2-2 The Active medium:

The active medium used in this work was an (Nd - glass) rod (7.5 cm) length and (0.6 cm) diameter the rod was fixed with two clamps inside the cavity.

2-3 The Reflector:

We used a circular cylindrical reflector consists of two parts, the first is fixed in the cover of the cavity which holds the linear flash lamp and the second part is situated under the laser rod when the is fitted above the cavity the reflector from circular cylindrical shape.

The cavity dimension are (15 x 3.5 x 3.5 cm) made from Aluminum metal which had high thermal diffusivity to dissipate the heat generated from the flash lamp.

2-4 Flash lamp:

A xenon flash lamp was used with pressure (P = 450 torr), total length (13.5 cm) and the active length (8 cm) i.e. the distance between the electrodes, the external diameter (D = 0.61 cm).

This type of cavity configuration is called close - coupled cavity. The lamp and the rod are placed as close together as possible [1], surrounds closely by the reflector.

3. Flash lamp characteristics:

Calculation of the lamp impedance parameter (k_o) which describes the impedance characteristics of the particular lamp .

The voltage - current relationship is described by [12].

$$K_o = \frac{V}{\sqrt{I}} \qquad ...(14)$$

From Fig (4), the intersection of current and voltage pulse are shown on an oscilloscope using current and voltage probe.

The resistance of current probe equals to (10 m Ω) and the value of voltage = 11 volt therefore the value of the current.

$$I = \frac{11}{10x10^{-3}} = 1100 Amp.$$

The value of the voltage at the intersection point = 1000 volt.

Hence From eq. (14) : $K_o = 30.15\ \Omega . (\text{Amp})^{0.5}$

To determine the value of K_o theoretically we use the damping factor equals $\alpha = 0.8$. Having:

$$\alpha = \frac{K_o}{\sqrt{V_o Z_o}} \qquad ...(15)$$

And

$$Z_o = \left(\frac{L}{C}\right)^{1/2} \qquad ...(16)$$

From the PFN :

$$L = 19.9 \mu H$$
$$C = 50 \mu F$$
$$Z_o = 0.63$$

Using equ (16)
And from equ. (15) :

$K_o = 28.39\ \Omega . (\text{Amp})^{0.5}$

To measure experimentally from fig (5) the current pulse duration is equals to $t_p = 84\ \mu s$ using the current probe .

From PFN C = 50 µf , therefor the inductance L equals to :

$$L = \frac{t_p^2}{9C} \qquad ...(17) \qquad L = 16 \mu H$$

From eq. (16) : $Z_o = 0.565\ \Omega$

And from eq. (15) and when $K_o = 30.15$ the damping factor $\alpha = 0.89$ Hence the rise time t_r equal to

$$t_r = (LC)^{\frac{1}{2}} \qquad \text{...(18)}$$

$$=28.3\,\mu s$$

And the current pulse duration ,

$$t_p = 3(LC)^{1/2} \qquad \text{...(19)}$$

The peak current I_p when the applied voltage $V_\circ = 2$ Kv is equal to:

$$i_p = 0.5\left(V_\circ / Z_\circ\right) \qquad \text{...(20)}$$

$$i_p = 1769.9\,Amp$$

Comparing the experimented with the theoretical results we can notified that the difference in the table (1)

	$t_p(\mu s)$	$tr(\mu s)$	$i_p(Amp)$	$Z_\circ(\Omega)$	$L(\mu H)$	$K_\circ$ $\Omega.(Amp)^{1/2}$	α
oretical	94.4	31.5	1587.3	0.63	16	28.3	0.8
erimental	84	28.3	1769.9	0.565	19.9	30.1	0.89

Table (1) the characteristics of the flash lamp

4. Measurements and Results:

4-1 Measurements of the output energy of the oscillator .

The theoretical value of O/P energy of the oscillator can be found from eq. (1) :

$$E_{out} = I_{sat}\tau_f A\eta(r-1)$$

$$I_{sat} = \frac{h\upsilon}{\sigma_{21}\tau_f}$$

$$h\upsilon = 1.8x10^{-19} J$$

$$\tau_f = 300\mu s$$

$$\sigma_{21} = 3.5x10^{-20} cm^2$$

$$A = 0.2826 cm^2$$

$$I_{sat} = 17714.2 {}^{W}\!/_{cm^2}$$

From eq. (2) :

$$\eta = 0.343$$

The inversion over threshold (r - 1) = 1.3
Substituting these value in eq. (1) we get :

$$\mathbf{E_{out} = 657mJ}$$

The experimental value of the oscillator output energy using joulemeter (Genetic ED - 200) equals 565 mJ.

This result shown a good agreement between theoretical and experimental value for the output energy of the oscillator, and the difference between them is related to the losses in the input pumping energy to the system.

4-2 Measurement of output energy of the amplifier .

The small signal gain coefficient is given by [10]

$$g_{0} = \Delta N \times \sigma_{21}$$

$g_o = 0.115\ \text{cm}^{-1}$

from eq. (11) :

$$G_o = 2.37$$

From eq. (8) and $\gamma = 1$ for 4- level system :

$$E_s = 5.31\ \text{J/cm}^2$$

From eq. (12) We have $E_i = 90.25$ J the pumping input energy and one can expect typically (0.5) % conversion of pump input energy to energy stored in the rod. [8,10]

Therefore $E_i = 0.45$ J and the output energy from the amplifier equals :

$E_{out} = 5.31 \ln \{1 + [\exp(0.45/5.31) - 1]2.37\}$

$E_{out} = 1013$ mJ = (1.013 J)

When a low input signal E_i such that $E_i/E_s << 1$ then

$G = G_0 = \exp(g_o l)$

$G = 2.3$

4-3: experimentally we got the value of the output energy from the amplifier equal to (900 mJ) by using joule meter.

Fig (6) shows show the variation of the input and output energy for both oscillator and amplifier. The overall efficiency of the oscillator equals to (0.606%), and from fig (7) the slope efficiency equals to (0.71%). The total efficiency of the osc-amp system equals to (1.18%).

From equ(13) the extraction efficiency $\eta_E = 12.7\%$. Fig(8) shows the pulse shape of the oscillator with pulse duration equals to (80 μs) using silicon - pin photo diode type (SGD-100) with rise time (4ns), an IR filter is used with transmission around 90% for 1.06 μm.

4-4: For optimal operation, the flash lamp for the amplifier stage has to be synchronized with that of the oscillator. This must be timed so that there is maximum population inversion in the amplifier when the beam from the oscillator inters it, the firing of the flash lamp for the oscillator, then is usually delayed relation to the amplifier flash lamp. The amount of this delay depend on the cct used and the particular flash lamp, but ordinary it is of the order of [50 - 100 μs][13].

In our work the delay time between the osc- amp was within [70 μs], which gave a good amplification for the oscillator pulse as shown in Fig(9), Fig(10), and the amplification factor around twice as much.

The stability of the system was shown in Fig(11) which gives a high stability of the system during the operation for different pulses when the input energy was fixed at suitable value.

Reference

[1] W. Koechner, " Solid – State Laser Engineering" Springer – Series in Optical Science, New York (1976).

[2] Petras, v .Avizonis & Ronald L.Grotbeek J. Appl. Phys. V.37 no. 2 1966 P.687

[3] L.M.Frantz and J.S.Nodvik , J. Appl. Phys. V.34 P.687 (1963).

[4] E.L.Steel & W.C. Davis , J. Appl. Phys. 36 ,348 (1965).

[5] J.I.Davis & W.R.Sooy, Appl. Optics 3,715 (1964).

[6] F.T.Arecchi & E.O.Schulz , laser hand book , vol 1 North-Holland Publishing Co. 1972.

مناف رشيد إسماعيل إطروحة ماجستير (تصميم وبناء المضخم الثاني لبضة [7]
ليزر النديميوم – ياك) الجامعة التكنولوجية (1995).

[8] N. N. Nassir (Design and Construction of Nd: YAG Oscillator – Amplifier Laser) Thesis Submitted to Military College of Engineering (1999).

[9] B. A. See "Optics and Laser Technology" Vol. 20 No. 6 PP (445-450) (19%).

[10] Koechner, W. Solid – State Laser Engineering, 2nd Ed, Springer-Verlag, New York (1992).

[11] O.Svelto ((Principles of laser)) 3rd edition plenum press, NewYork & London 1989.

[12] J.H.Gonez, J. Appl. Phys. 36, 742 (1965).

[13] E.L.Steel ((Optical laser in Electronics)) John – Wiley & Sons 1986.

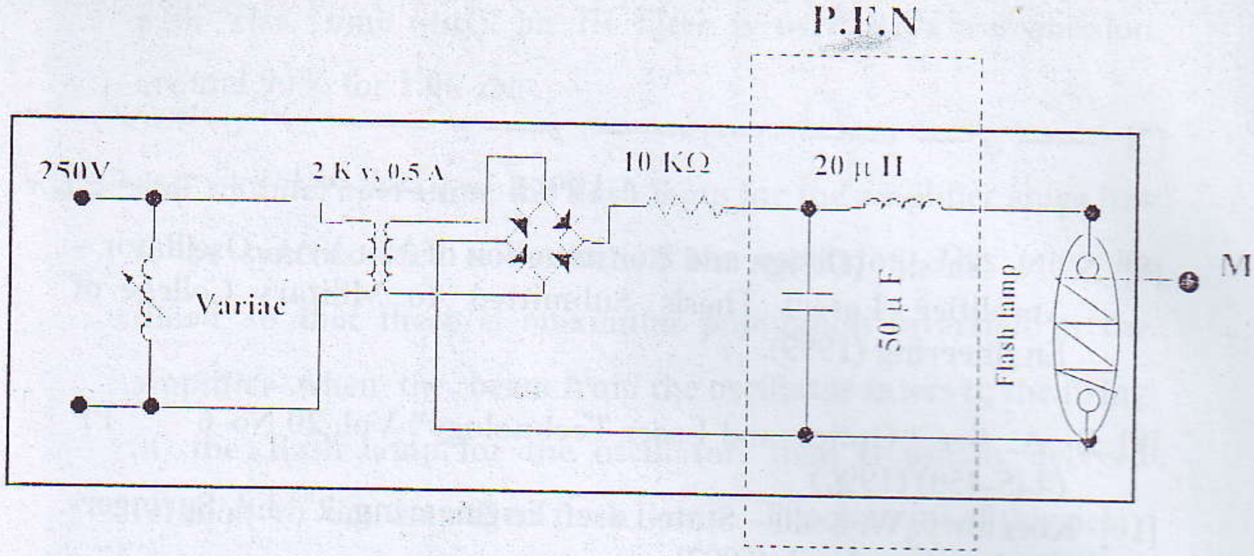


Fig. (1) 2 KV (D.C) Power Supply & Charging Circuit

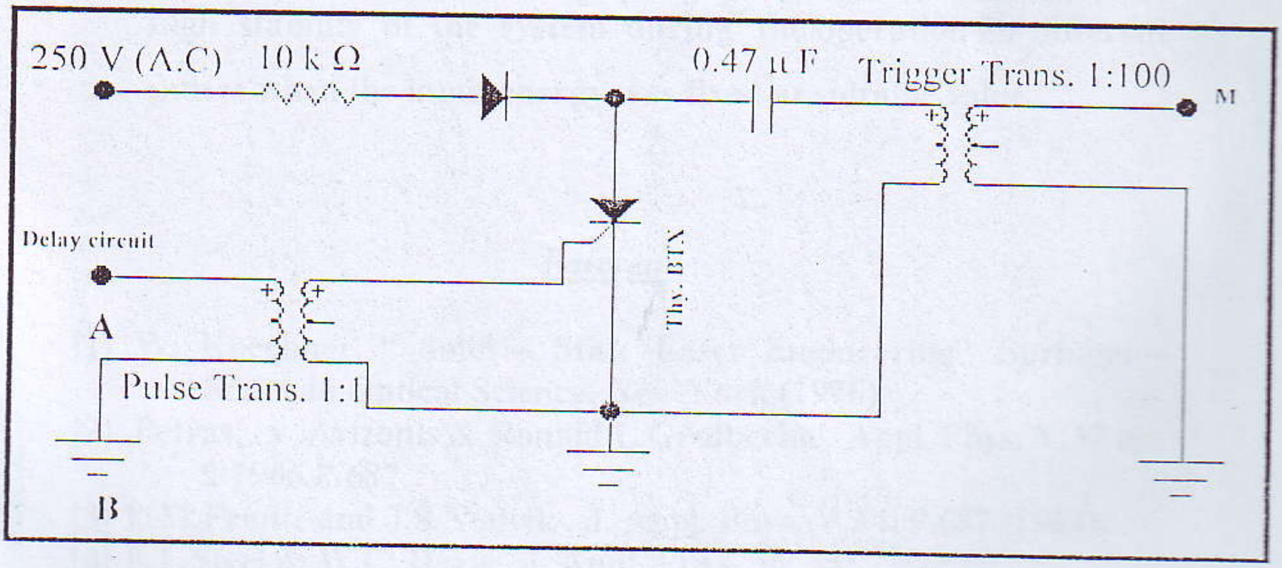


Fig. (2) Trigger Circuit

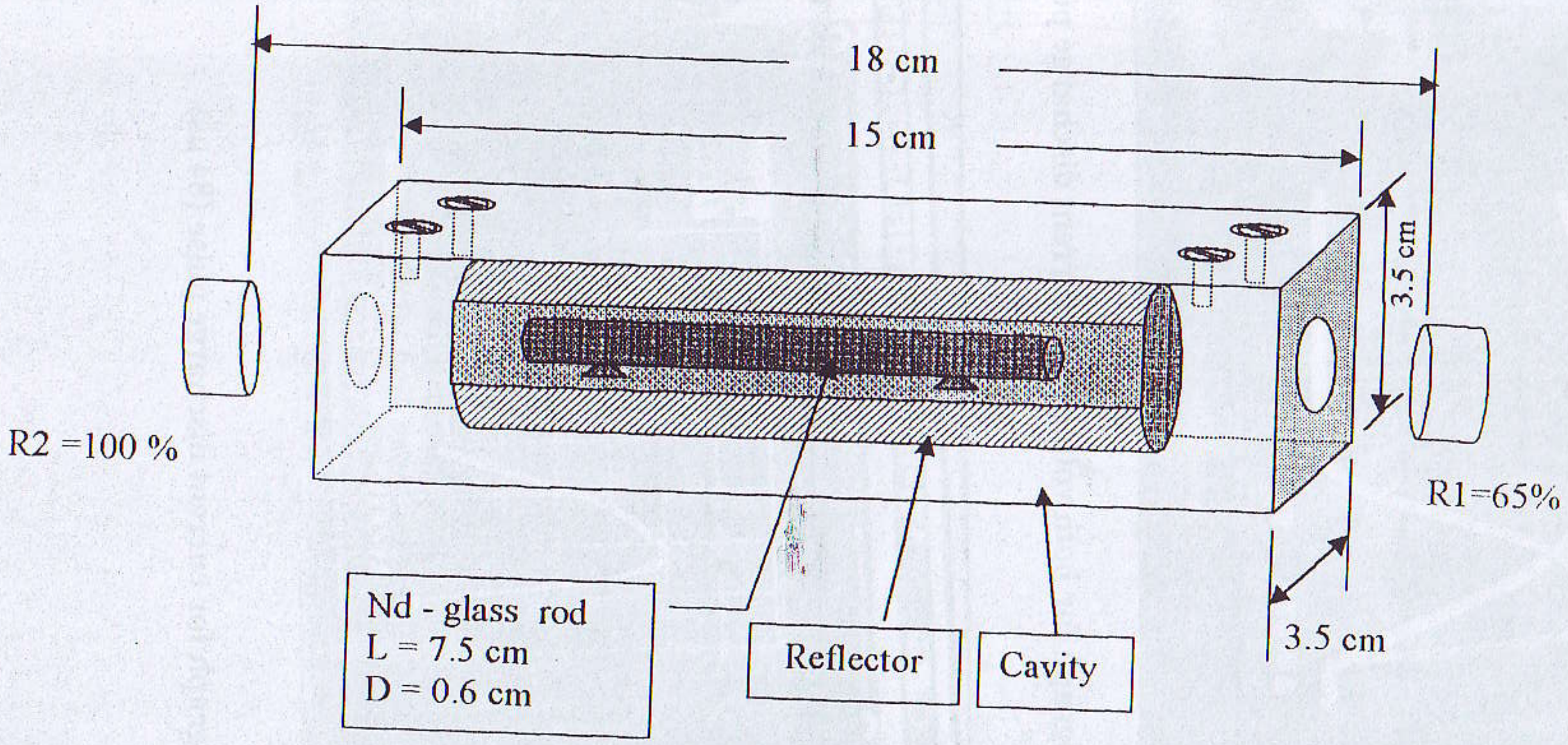
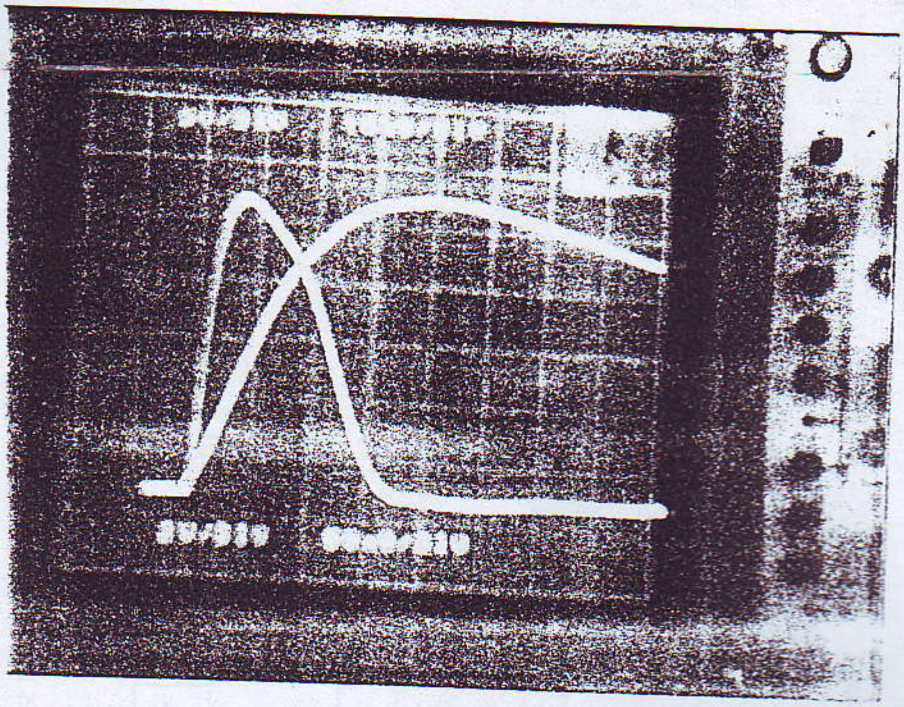
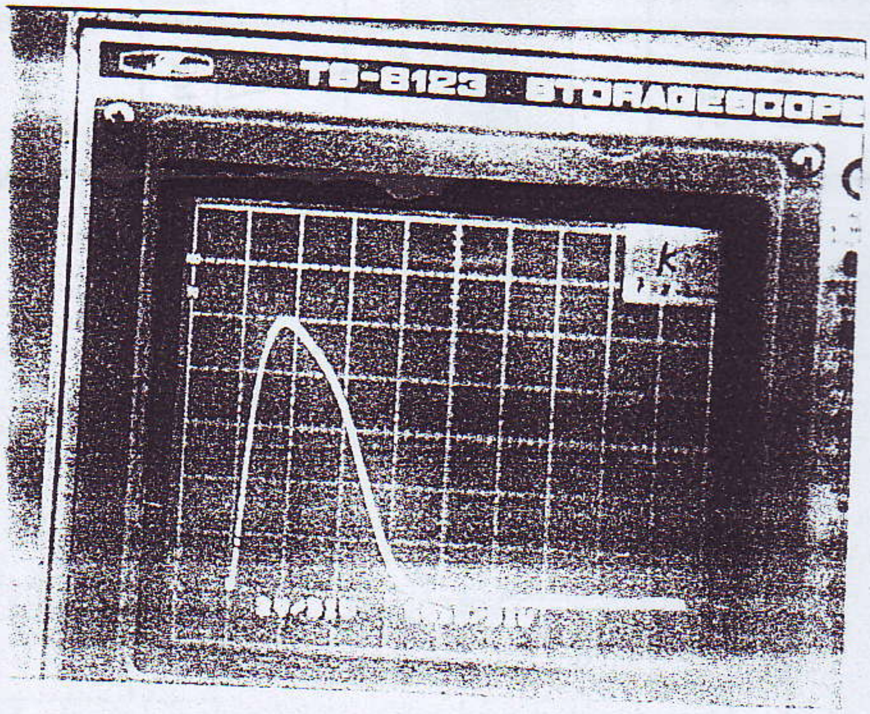


Fig (3) Optical resonator of Nd -glass oscillator



Fig(4) Photograph for both voltage and current discharge pulses.



Fig(5) Photograph for current discharge pulse (84 µs).

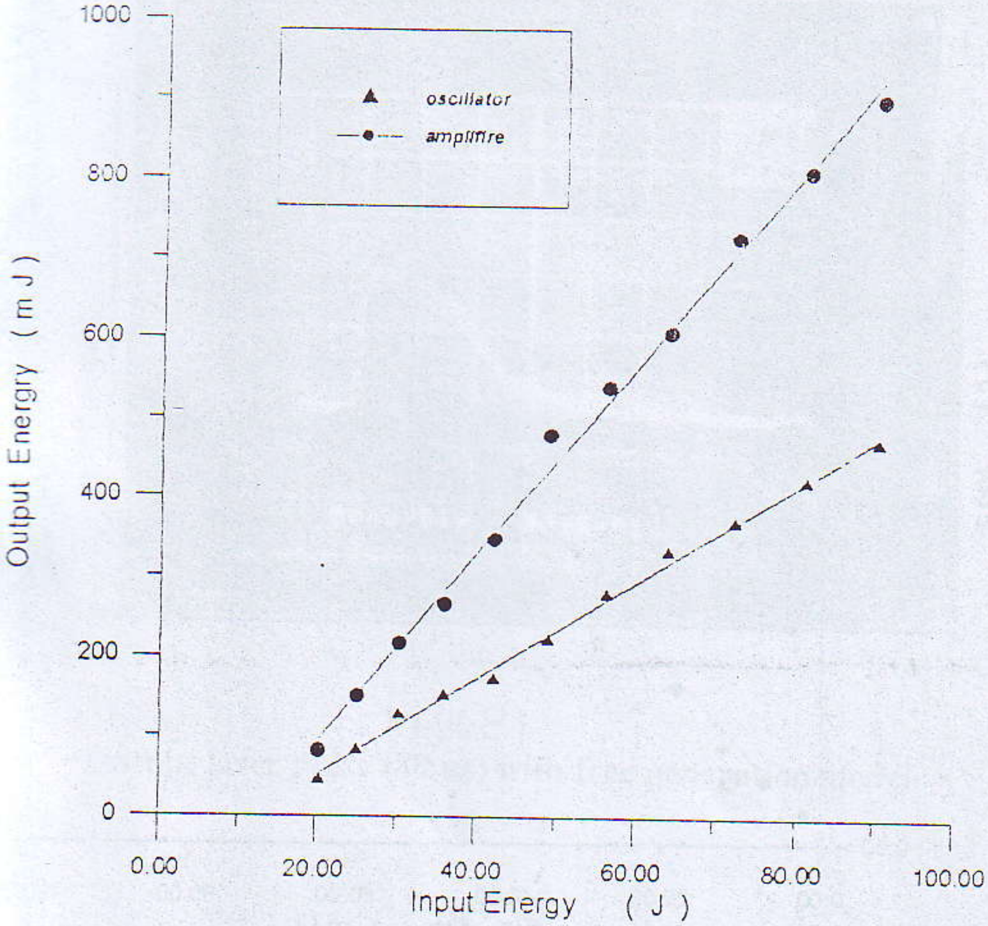


Fig (6) The variation of Output Laser Energy as afunction of pumping energy for both oscillator & amplifire

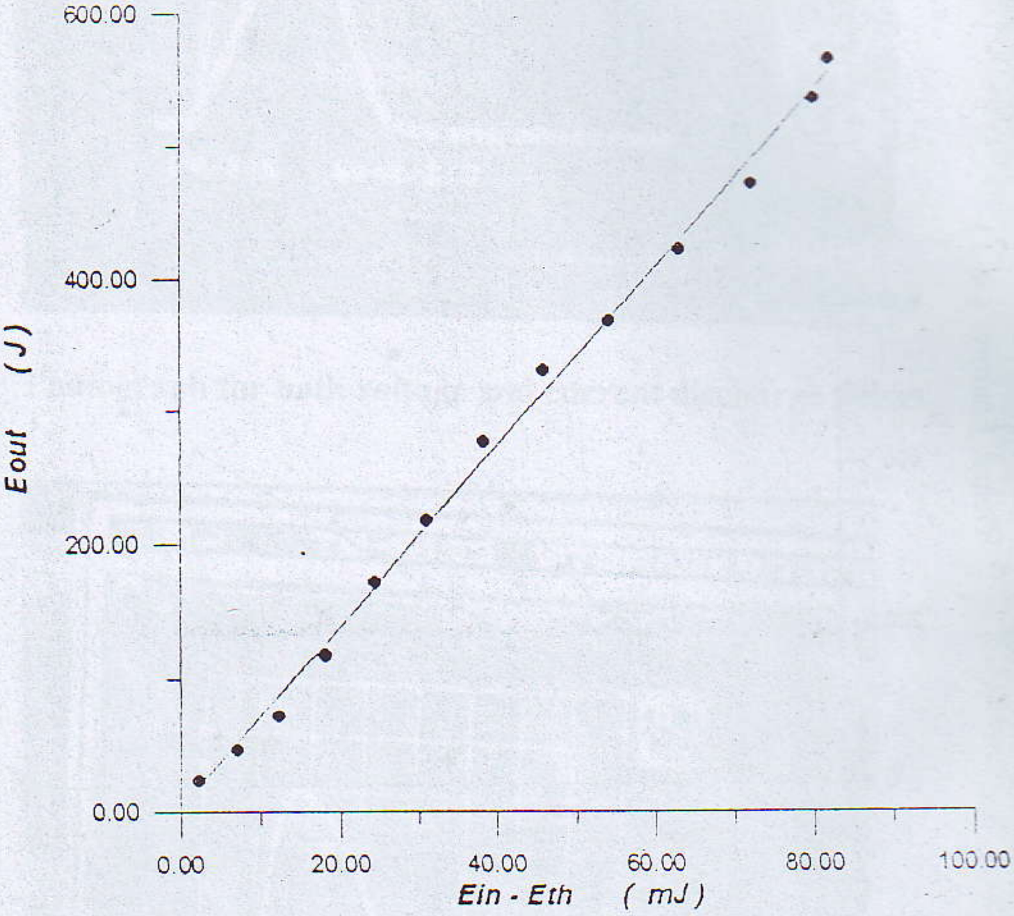


Fig (7) variation of output Laser energy as afunction of input energy for oscillater R = 65 %

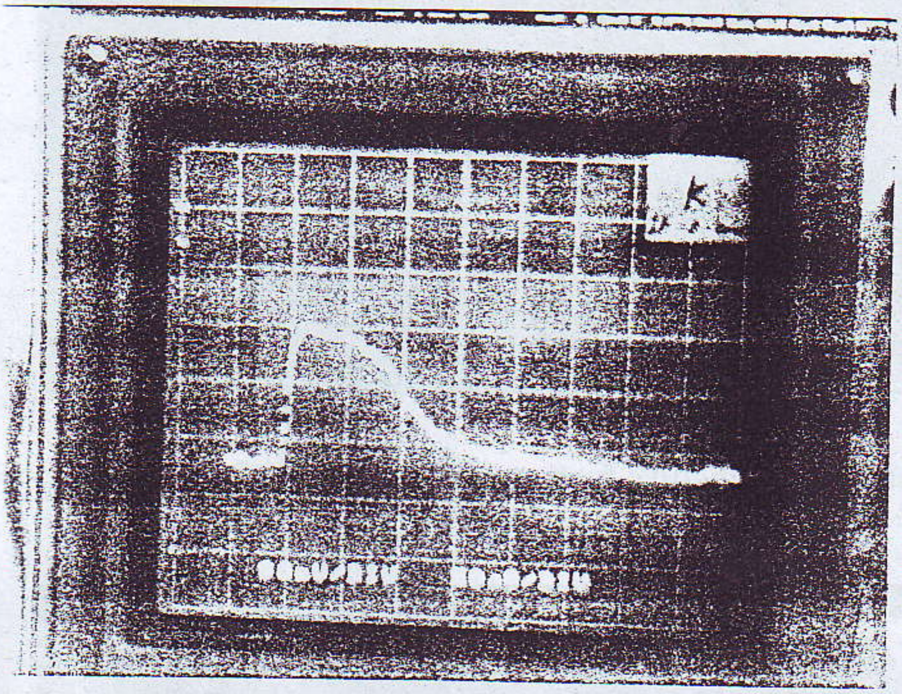


Fig (8)

Output laser pulse (80 μs) with free generation mode.

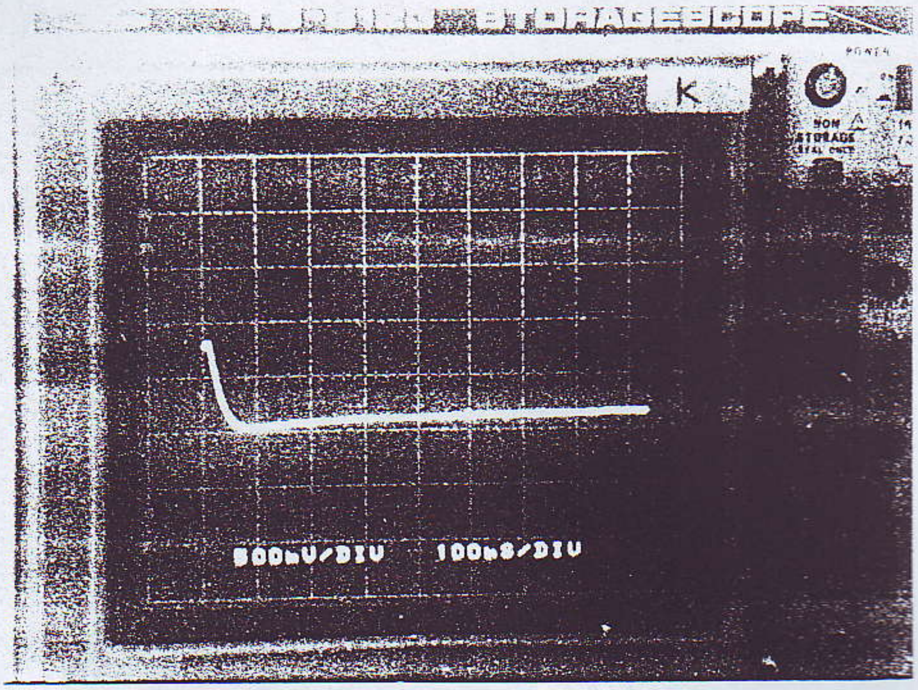
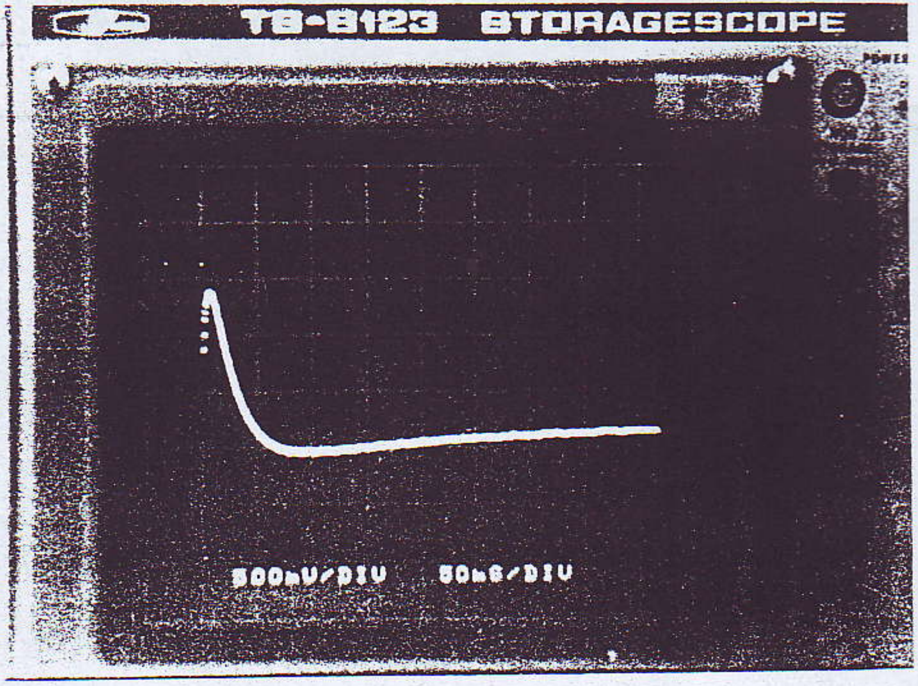


Fig ([illegible]) Photographic picture for output laser energy for oscillator system.



- Photographic picture for output laser energy for (oscillator – amplifier) system.

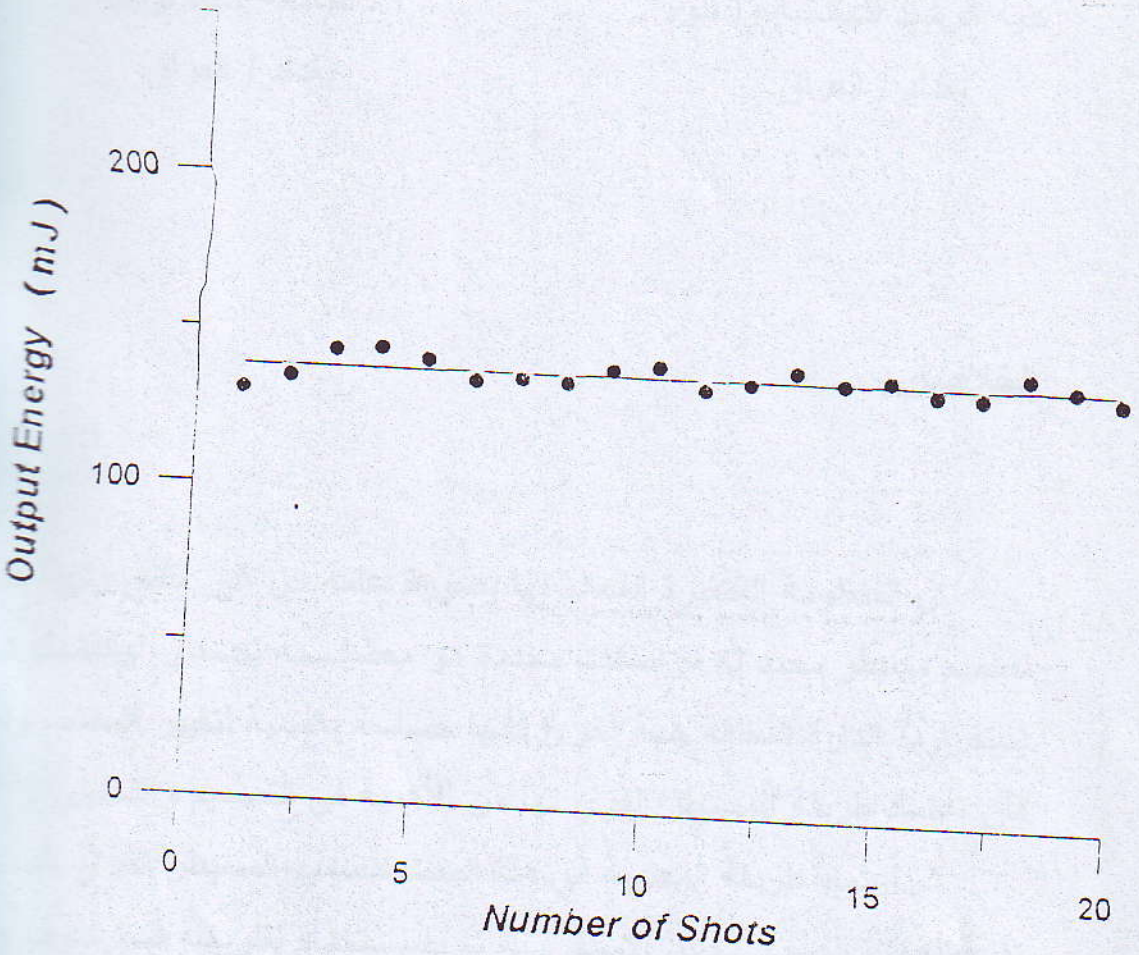


Fig (11) The stability of the system at fixed input energy