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Q-SWITCHED LASER AS A SOURCE FOR THOMSON SCATTERING FROM A HOLLOW CATHODE ARC

by
Kenneth J. Dick

A Thesis
Submitted to the Faculty of Graduate Studies
through the Department of Physics in
Partial Fulfillment of the Requirements
for the Degree of Master of Science
at the University of Windsor

Windsor, Ontario
1967

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ABSTRACT

A Q-switched laser system was considered as a light source for Thomson scattering from a hollow-cathode gas discharge. An investigation was made of the effects on the system under normal oscillation, when the parameters temperature, cavity length, and input pumping were varied. Phthalocyanine and cryptocyanine dyes in solution were studied as passive Q-switching elements. Attempts were made to optimize the system for maximum peak power by varying the reflectivity of the external cavity mirror and the concentration of the Q-switch dye.

It was found that most of the available peak power was obtained using dye solutions of between 30% transmission and 60% transmission and an external cavity mirror of approximately 50% reflectivity. Medium pumping of the laser system provides a minimum power of 1 megawatt for repetitive firings. Under hard pumping, peak powers of at least 4 megawatts are available.

These results show that the laser system developed is adequate as a light source of sufficient power output for detectable scattering from the arc discharge.

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ACKNOWLEDGEMENTS

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I am grateful to Mr. R. Walton for preparation of the Q-switch dye solutions and absorber cells. It is a pleasure to acknowledge the valuable discussions with Dr. B. Kibble and Dr. P. Maker.

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I. INTRODUCTION

The necessity of using a Q-switched laser to perform a Thomson scattering experiment on a plasma can best be seen by consideration of some of the problems inherent in the scattering process itself.

The potical scattering technique for plasma diagnosis is similar to radar. A pulse of light is sent out and the light scattered out of the beam is received. Measuring the amount of Thomson scatter as a function of angle and frequency, determines the electron and ion densities and temperatures. Difficulties arise mainly because of the small Thomson cross-section of 7.94×10^{-26} cm^2. Such a small fraction (10^{-13}) of the incident radiation is scattered that only very high intensity light sources are suitable. The recently developed solid state pulsed laser with its high degree of monochromaticity, coherence, and power density has made possible detection of the weakly scattered signal against the high luminosity plasma background[1]. For example, 4 joules of ruby-laser light scattered from a plasma density of 10^{13} cm^{-3} yields about 10^5 photons per unit solid angle. A 2% response from a photocathode with an S-20 surface gives several hundred photoelectrons which would allow a signal-to-noise ratio of five to ten[2].

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Although results of Thomson scattering have been reported[3] using high energy lasers operating in the normal mode with pulse lengths of approximately 1 msec, plasma diagnosis with high power Q-switched lasers having pulse widths of 30-100 nsec offer several advantages, not the least of which is reduction in the possibility of electron production by photoionization. It has been observed[4] that an increase in plasma luminosity (indicating an increase in electron density) took place during a 0.5 msec, 20 joule normal laser pulse. This was thought to be caused by photoionization of excited atoms. The density of atoms in the excited state is maintained during the laser pulse by collisional excitation; a gradual pumping of the continuum states results until the rate of ion loss is equal to the pumping rate, and an equilibrium is established at a higher electron density. This occurs in a time equivalent to the ion lifetime. If this is long compared with the duration of either a normal ($\sim$0.5 msec) or Q-switched ($\sim$50 nsec) laser pulse, the ionization should be less for the Q-switched pulse by at least the ratio of the energies of the two kinds of pulses, or 1:20. In general, calculations show[5] that a short laser pulse is desirable, allowing satisfactory signal-to-noise ratio with less total energy.

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Design of a Q-switch laser system involves choosing between active switching devices such as Kerr cells and rotating prisms, and passive switches such as bleachable absorbers and thin film dyes, all of which offer comparable power outputs.

Passive Q-switch systems offer the advantage of no moving parts or critical alignment problems and no external fields. Once the giant pulse begins it is not cut off as in the case of some rotating mirror systems. Hence the total dissipation of population excess is limited only by the unspoiled Q of the system. There are no unusual limitations in power handling capabilities since what remains immediately after bleaching of the dye solution or burning of the film is a conventional laser geometry. Active devices require external synchronization but passive switching techniques are self-synchronizing in that Q-switching action occurs close to the time for maximum gain.

The application of a Q-switched laser system as a plasma diagnostic tool led to the choice of a passive switch. The characteristic control and pulse timing offered by active switching systems was considered unessential for observing Thomson scattering from the hollow cathode gas discharge.

Two types of passive switches were initially

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investigated; namely, thin-film Q-switch plates and reversible dye solutions. When struck by a laser beam the former undergo primarily a thermal molecular dissociation to a permanently transparent state, while the latter undergo a nondestructive optical saturation process which allows repetitive operation.

Although the thin films allowed slightly greater energy output than the absorber dye solutions, the pulse widths were also greater by 30%, so that the effective power output for both types was approximately the same. Each thin-film plate gave about 25 pulses,with the device having to be moved after each pulse. The absorber dye solutions which could be used repeatedly were finally chosen as Q-switch elements.

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II. THEORETICAL CONSIDERATIONS

In general, solid state pulsed laser systems are made up of a resonant Fabry-Perot cavity with reflecting surfaces between which the laser beam is amplified, an amplifying medium consisting of two atomic states with energy separation corresponding to the desired output frequency, and a means of overpopulating the upper level with respect to the lower, usually done by exciting atoms from the ground state to the higher energy state either electrically or optically.

Laser action occurs at a certain level of excitation or population inversion called the threshold where the gain of the system is greater than the losses. A consideration of the threshold condition indicates the reason behind the method used to obtain Q-switched operation.

Consider a material, for example ruby with a monochromatic beam of frequency ν travelling in the positive x-direction through a layer of atoms of thickness dx. There are n_1 cm^{-3} atoms in the lower state and n_2 cm^{-3} atoms in the upper state capable of absorbing and emitting this radiation respectively. Neglecting the effect of spontaneous emission since it takes place in all directions

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and does not contribute significantly to the beam, the change in power per unit area of the beam, dP is

$$(1) \qquad dP = h\nu dx(n_1T^i_{12} - n_2T^i_{21})$$

where h is Planck's constant, and T^i_{mn} the induced transition rate is given by

$$(2) \qquad T^i_{mn} = B_{mn}\epsilon$$

with B_{mn} being the Einstein B coefficient for induced transitions from level m to level n and ϵ the energy density.

From (1) and (2),

$$(3) \qquad \tilde{P} = h\nu V\epsilon (n_1B_{12} - n_2B_{21})$$

where V is the volume of the substance illuminated by the beam and $\tilde{P}$ is the power absorbed or emitted depending on whether n_1B_{12} is greater than or less than n_2B_{21} respectively.

Now the quantity describing the power loss P_c of a resonant cavity is its quality factor Q defined by the relations:

$$(4) \qquad P_c = \frac{dE}{dt} = -\frac{2\pi\nu E}{Q}$$

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where ν is the resonant frequency and E is the energy in the cavity. For a cavity whose resonant frequency is set equal to that of the atoms which can emit power, the condition $\tilde{P} = P_c$ gives the minimum population density required for oscillation, viz;

$$n_2 - n_1 \frac{B_{12}}{B_{21}} \doteq (\hbar Q B_{21})^{-1} \qquad (5)$$

with $V\epsilon = E$.

Giant pulse operation is characterized by very high peak power output in the form of one sharp pulse. This requires very high population inversion. However, the induced emission during normal laser oscillation will decrease the lifetime of the Cr^{+3} ions in the metastable level and this limits the population inversion for a given pump level, hence limiting the peak power. Also, high pumping past threshold is difficult as can be seen from equations (3) and (4). The output power $\tilde{P}$ is proportional to the population inversion Δn. Also, Q is proportional to $\tilde{P}^{-1}$. Now, for high peak power large Δn is required, as well as a high Q for low dissipation to provide a large stimulating photon flux.

Ideally then, a low Q must first be provided to allow buildup of large Δn, followed by a switch to a high

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Q value to allow the wave to build up.

This Q-switching is accomplished by introducing a loss into the system in the form of a liquid absorber which has an atomic transition at the same frequency as the stimulating radiation in the cavity. At the start of the pumping, the Q of the optical resonator is maintained at a low value by absorption of the photons so that the system cannot oscillate. After the excited state of the active medium has been populated to some value n_o, the Q is very suddenly switched to a high value by the bleaching of the dye solution which then becomes almost perfectly transparent to the laser light. Since, for the population at threshold, $n_{th} \propto Q^{-1}$ (equation (5)) and $n_o > n_{th}$, it is apparent that after the switching there is a superabundance of excited atoms. This situation creates an enhanced regeneration with the result that the system will discharge its energy very quickly in the form of a giant pulse.

The threshold condition for establishing oscillation may be arrived at from the requirement that the amplification during one passage of the wave through the medium is sufficient to replenish the loss, viz;

(6) $$e^{\alpha L} = R^{-1}$$

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where α is the negative absorption (gain) per cm, L is the distance between the end reflectors and R is an equivalent reflectivity including all forms of optical loss. For αL very small and R close to 1,

(7) $$\alpha L = 1 - R$$

Lambert's law governing the intensity of light in moving a distance x through a medium is

(8) $$P = P_o e^{-kx}$$

where k is the absorption coefficient in cm^{-1}.

From (1), (2), and (8), the absorption coefficient $k = -\alpha$ may be expressed as

(9) $$k = -\frac{1}{P}\frac{dP}{dx} = \frac{h\nu}{v}(n_1 B_{12} - n_2 B_{21})$$

where v is the velocity of light in the medium obtained from the Poynting vector $\vec{P}$ which is related to the energy density by

(10) $$\vec{P} = \vec{p} v \epsilon \quad .$$

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Now, the number of cavity modes per unit volume within an atomic line of Lorentzian shape with half-width $\Delta\nu$ and peak value $(\pi\Delta\nu)^{-1}$ is

(11) $$\rho = \frac{8\pi^2\nu^2\Delta\nu}{v^3} \quad .$$

Also, the Einstein A coefficient for spontaneous transitions is related to the B coefficient by

(12) $$A_{mn} = \left(\frac{8\pi\nu^2}{v^3}\right) h\nu B_{mn} \quad ,$$

and

(13) $$B_{21}g_2 = B_{12}g_1$$

with g_1 and g_2 being the degeneracies of the respective levels, so that the negative absorption coefficient becomes

(14) $$\alpha = \frac{A_{21}}{\rho v}\left(n_2 - n_1\frac{g_2}{g_1}\right) \quad .$$

Equation (6) for the threshold condition and equation (14) for the gain coefficient at resonance will be considered in evaluating the results.

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III. DESCRIPTION OF APPARATUS

The basic laser system consisted of a Lear Siegler Inc. laser console and a cylindrical head containing a 3" long, ¼" diameter TIR 90° ruby rod pumped by a helical Xenon flashlamp. The general arrangement is shown in Fig. 1. Energy stored in a 475 μf condenser bank was discharged across the flashlamp by a 20 KV triggering spike.

Cooling of the ruby crystal was accomplished by pumping liquid air vapour from a 4 litre dewar through a flexible hose connected to a length of glass tubing surrounding the rod. The flow rate was varied by dissipating heat through a resistance immersed in the liquid air. An iron-constantan thermocouple in the flexible hose and connected to a spot galvanometer acted as the temperature monitor.

The external cavity mirrors were Perkin-Elmer optical flats with calibrated transmissions of 1% to 85%. The mirror holder was designed for adjustment in both x and y directions of 1 minute of arc per 0.01 mm on a micrometer screw. Provision was made for the cup holding the optical flat to be rotated so that any mirror damage could be removed from the path of the output beam.

Energy measurements were taken by focussing the

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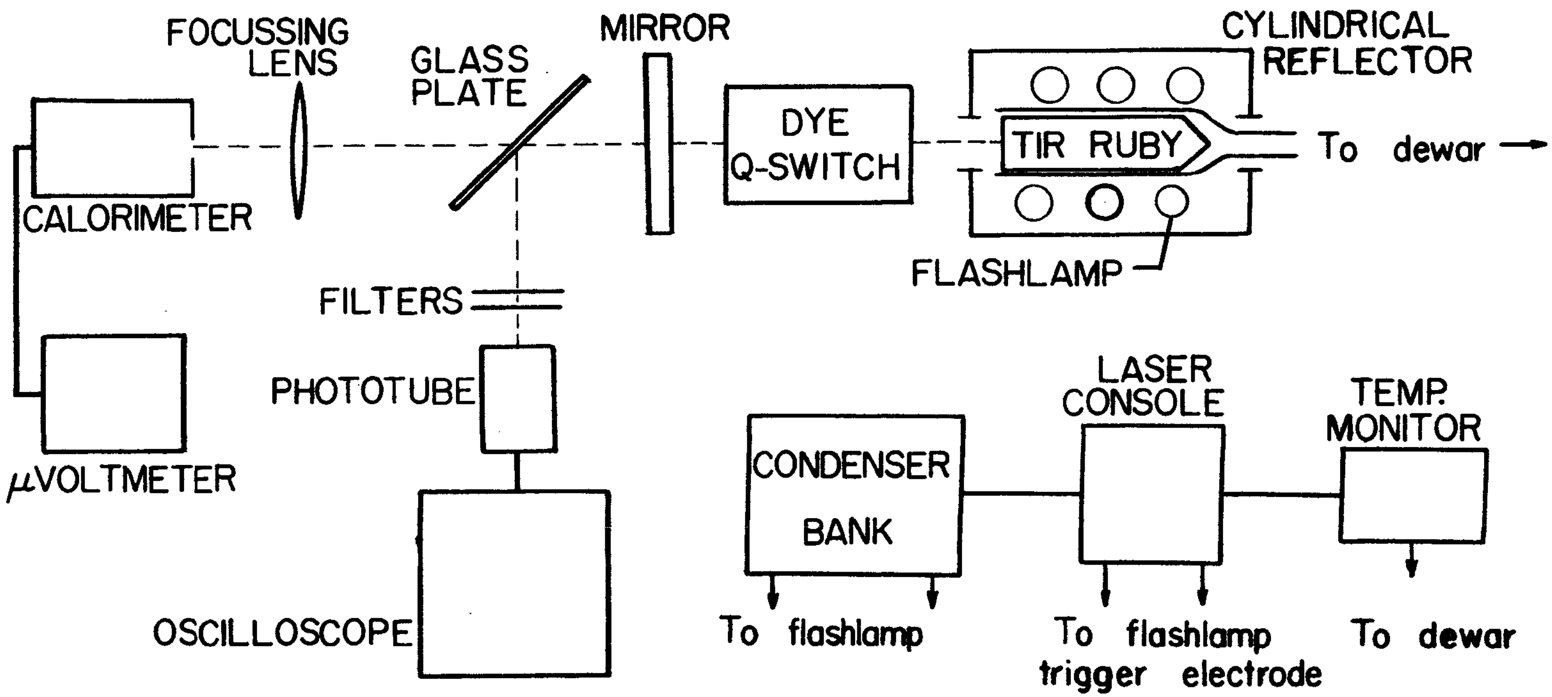

Fig. 1 Block diagram of the apparatus

output radiation into a Maser Optics calorimeter of sensitivity 0.016 joules per μvolt connected to a Hewlett-Packard μvoltmeter.

A 925 phototube with an S20 surface for maximum sensitivity at the laser wavelength (6943A) was used to detect the pulse which was displayed on a Tektronix 555 oscilloscope. To attenuate the output beam, heat resistant Corning glass filters were used.

Optical alignment of the system was achieved using a Bendix He-Ne gas laser and a Raytheon autocollimator.

The saturable absorbers used in the investigation were phthalocyanine in nitrobenzene solvent and cryptocyanine in methanol. Stock solutions of various concentrations were used in glass absorption cells with 1 mm and 10 mm path lengths. An IBM 25 mm cell containing a phthalocyanine solution was also employed as a Q-switch.

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IV. EXPERIMENTAL PROCEDURE

An investigation was made of the effect on threshold and energy output of the laser system in the normal oscillation mode when the parameters, input energy, temperature, and cavity length were varied. In each case where the units of a figure are given as "relative units" or "arbitrary units", the energy was measured with a 0.1 μfarad condenser across the output load of the phototube to integrate the spiking of the laser. The oscilloscope trace was photographed and the area measured using a planimeter. In obtaining the trace of the laser pulse, best results were achieved using a 10K ohm load with the phototube for normal oscillation and a 1K ohm load when operating in the Q-switch mode.

Initial attempts at optimizing the laser geometry for peak power in the Q-switch mode made use of the theory of laser pulsing by a saturable absorber[6] which predicts that the optimum reflectivity of the end mirror for maximum peak power and maximum energy in the pulse approximately coincide. It was assumed that complete saturation of the dye occurred and the only losses to be considered would be those present in a laser geometry with external mirror under normal oscillation plus the loss contribution of

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absorber cell and solvent.

Extending the assumption further, a method of determining the optimum reflectivity for maximum energy under normal oscillation[7] was investigated without the absorber cell in the cavity since it was thought that this would be a constant loss at all pump levels and the results could then be simply multiplied by the constant loss factor of the cell plus solvent for the Q-switch mode.

The transmissions of the dye solutions at 6943A were measured using a square 10 mm cell in a spectrophotometer. The results are given in Table 1.

TABLE 1

Transmission of Q-switch dye solutions

Dye Molecule	Concentration (10^{-6} Molar)	Percent Transmission
Phthalocyanine	30	27
Phthalocyanine	10	56
Phthalocyanine	Unknown*	50
Cryptocyanine	20	33

*sealed IBM 25mm cell

To check the effects of absorber concentration on the system, a 10 mm cell was filled with 6 ml. of methanol and measured amounts of cryptocyanine from a 10^{-4} molar stock solution were added to this cell using a pipette.

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V. EXPERIMENTAL RESULTS

A typical result for the output energy as a function of input energy is given in Fig.2 for a cooling temperature of 122°K (8.0 mV on temperature monitor) and no external cavity mirror. This result is greatly dependent on temperature of the ruby as indicated by the plot of energy output against temperature in Fig.3. The temperature range covered corresponds to values of 7.5 mV-8.9 mV on the temperature monitor of the laser console. The lowest temperature which could be maintained over a practical length of time was for a setting of 8.5 mV corresponding to 114°K.

The selection of a cavity length for the Q-switch mode of operation lead to an investigation of the effects of cavity length on oscillation (in the normal mode). An external cavity mirror of 75% reflectivity was used to obtain the results given in Fig.4. A cavity length of approximately 12 cm was finally chosen for convenient insertion of the different absorber cells.

The following technique for optimizing a laser cavity for maximum output energy[7] was investigated for a low pumping input of 2440 J. In this method, the equation for the energy output per unit volume of the ruby is derived

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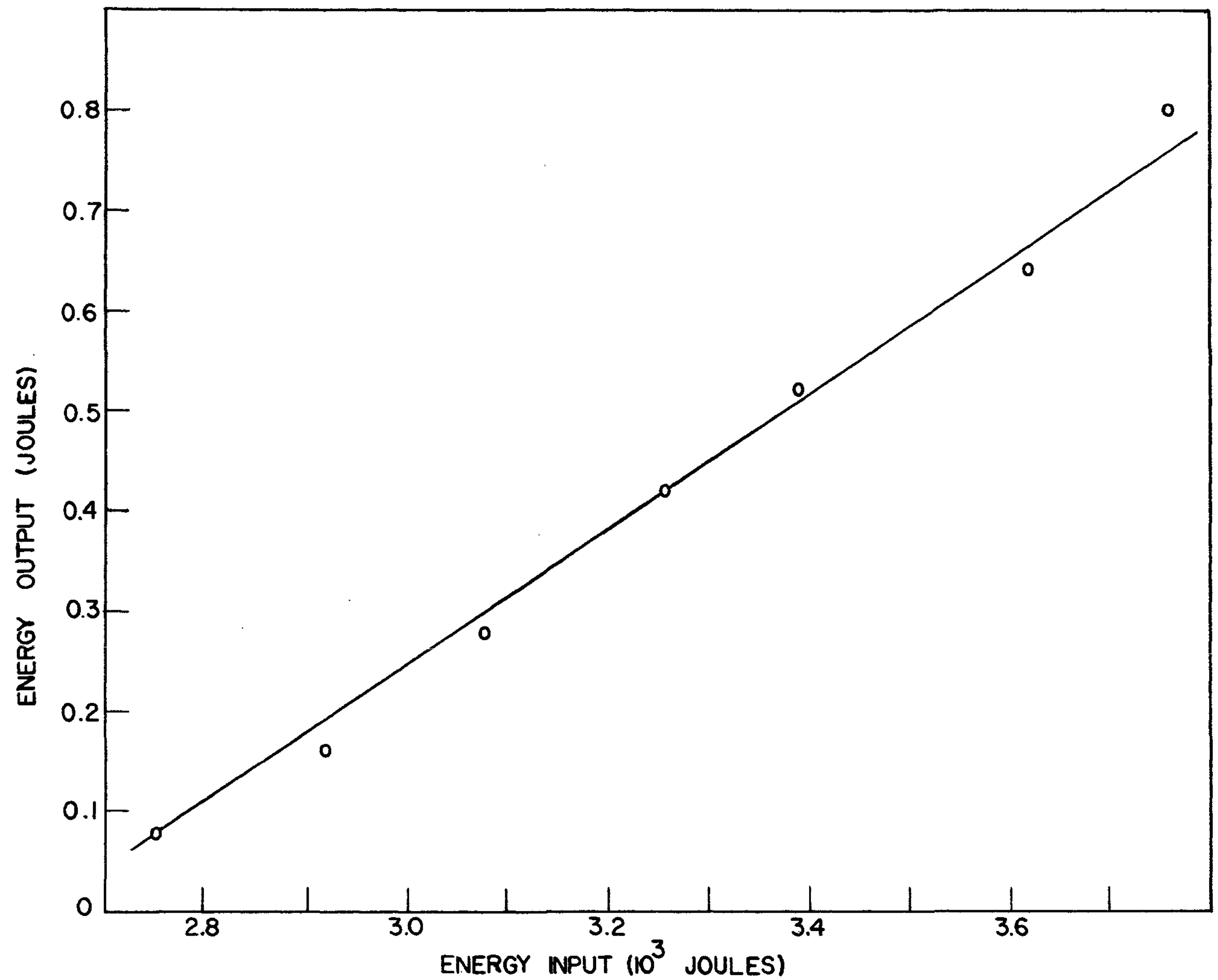

Fig.2. A plot of energy output against energy input for normal oscillation. No external mirror, temperature setting 7.5 mV.

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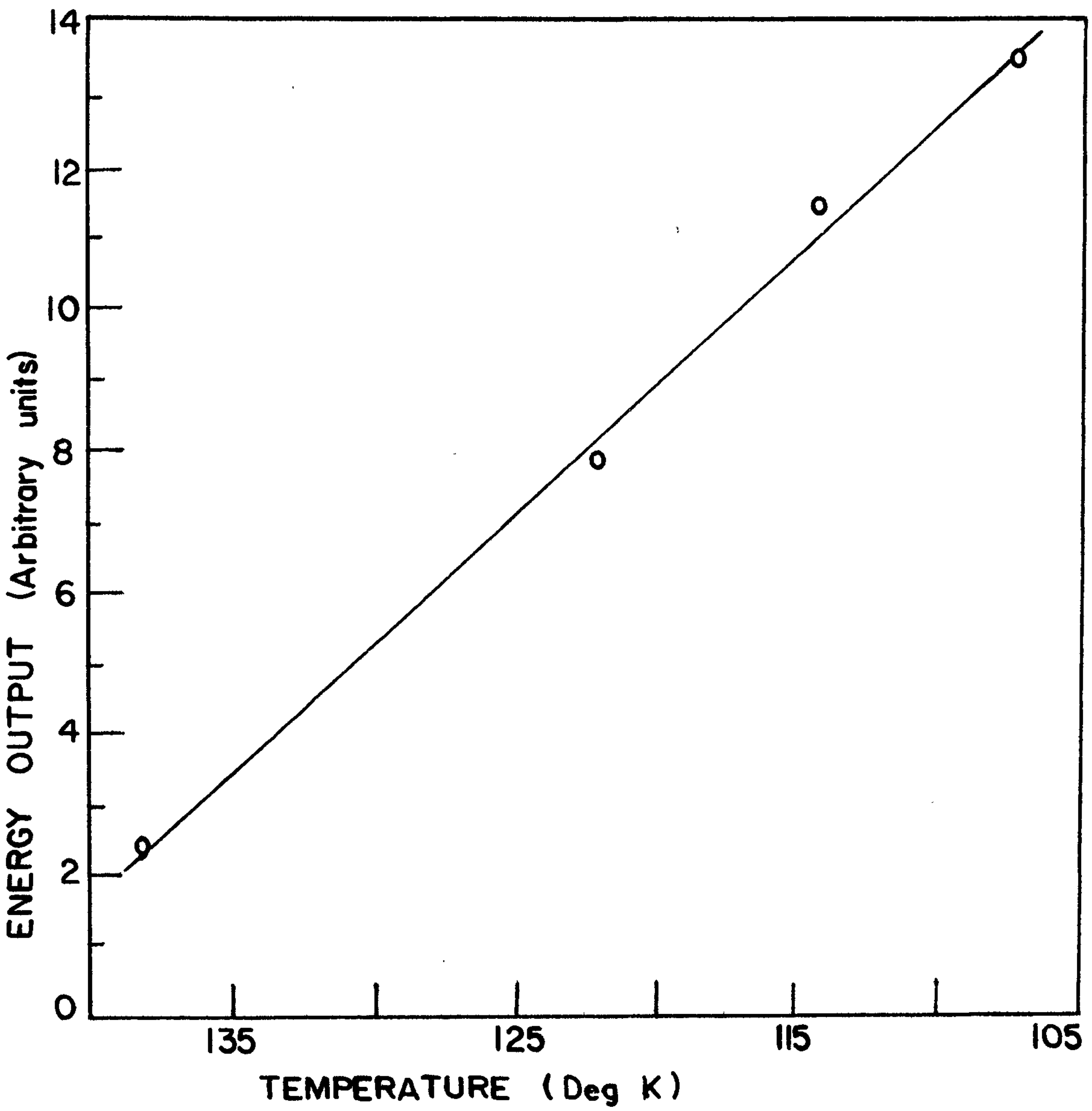

Fig.3. A plot of energy output as a function of temperature for normal oscillation. (constant input of 2432 joules, no external mirror)

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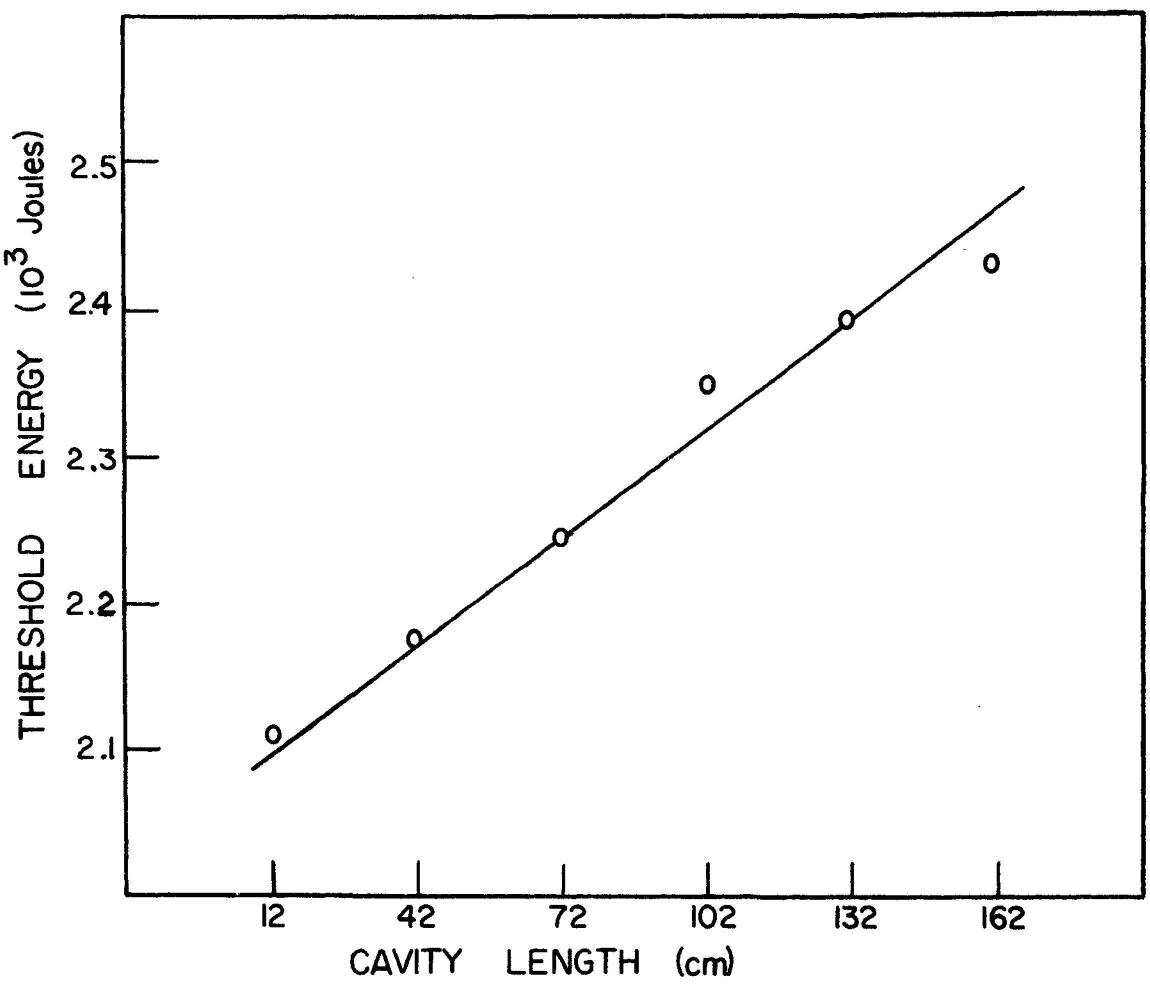

Fig.4. A plot of threshold energy against cavity length. (temperature setting 8.5 mV, 75% external mirror)

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analytically as a function of the internal cavity loss γ_{in} and the reflectivity of the output mirror γ_{ext}. The unknown quantities in the expression are determined from a set of three simultaneous equations formed by adding a known cavity loss to the inherent cavity loss, in the form of an attenuator. The simultaneous equations are set up by first measuring the energy output with no attenuator and then making two more energy output measurements with two attenuators, each of different value. The value obtained for the internal cavity loss is then used in an expression for the optimum reflectivity.

The theoretical curve in Fig.5 was plotted for an internal cavity loss of $\gamma_{in} = 0.24$, determined with glass microscope slides of 78.3% transmission and 71.8% transmission. The bars used to indicate the experimental values take into account the fluctuations of the μ voltmeter.

Fig.6 gives the output energy as a function of reflectivity for three different pump levels corresponding to 2440 J, 2750 J, and 3080 J input. Fig.7 shows the optimum reflectivity obtained with a 1 mm cell containing nitrobenzene only in the cavity, for pump levels of 2750 J and 3080 J with a temperature setting of 8.0mV. The maximum reflectivities obtained in Fig.8 were for the system in the giant pulse configuration pumped at 2750 J for a

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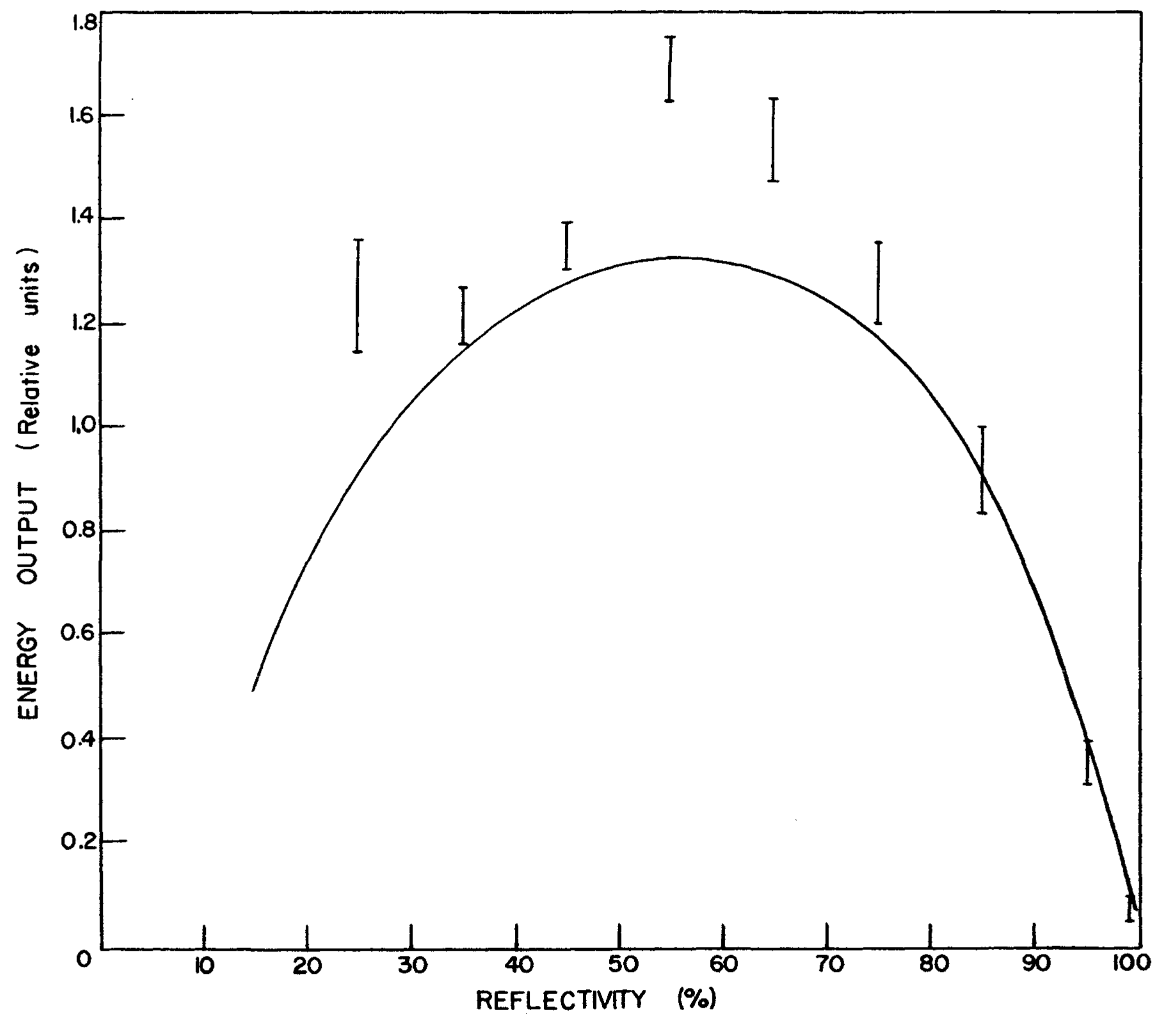

Fig.5. A theoretical and experimental plot of energy output against mirror reflectivity with no absorber cell in cavity. (temperature setting 7.8 mV, 85% mirror)

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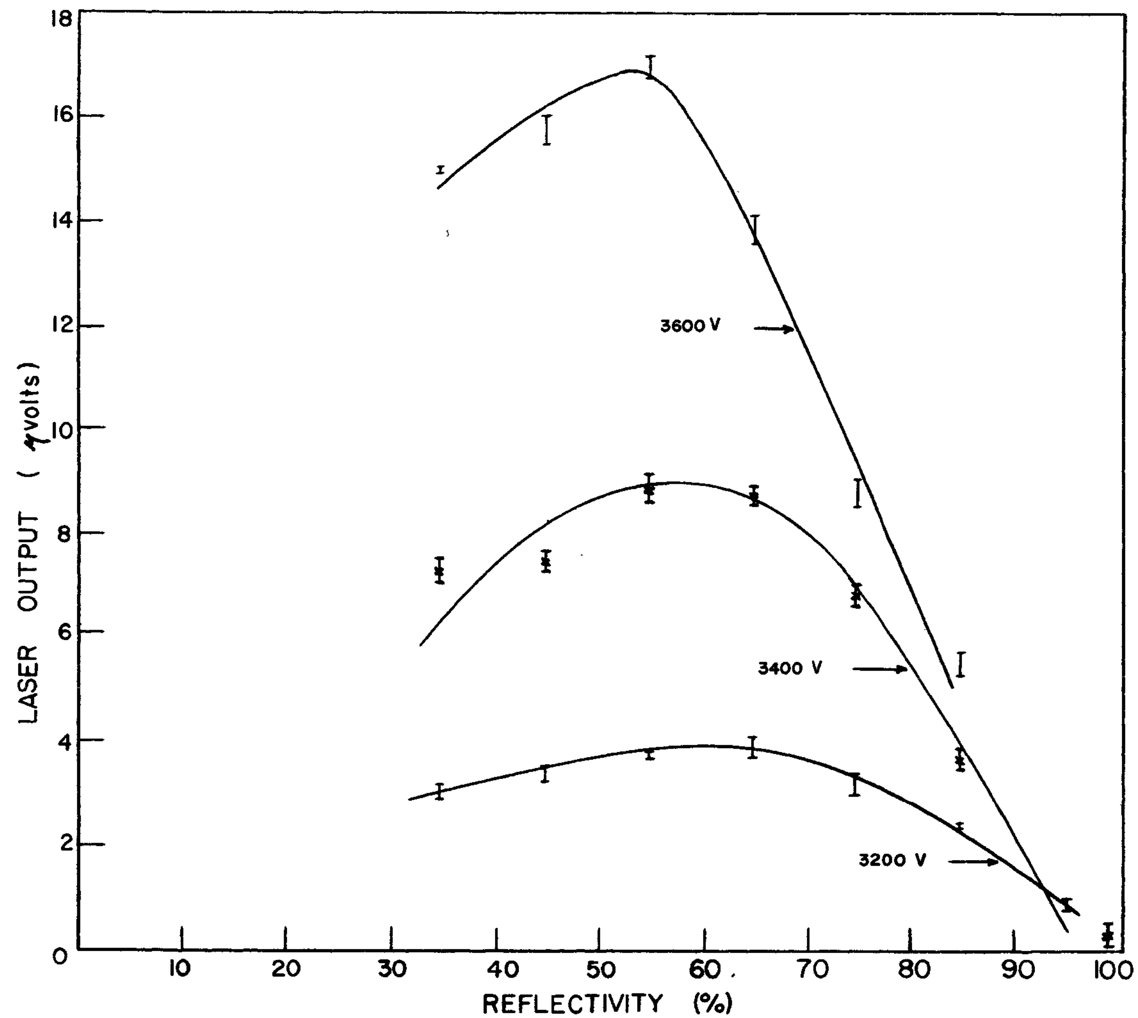

Fig.6. A graph of laser output against mirror reflectivity for 3 different pump levels. (temp. setting 8.0 mV)

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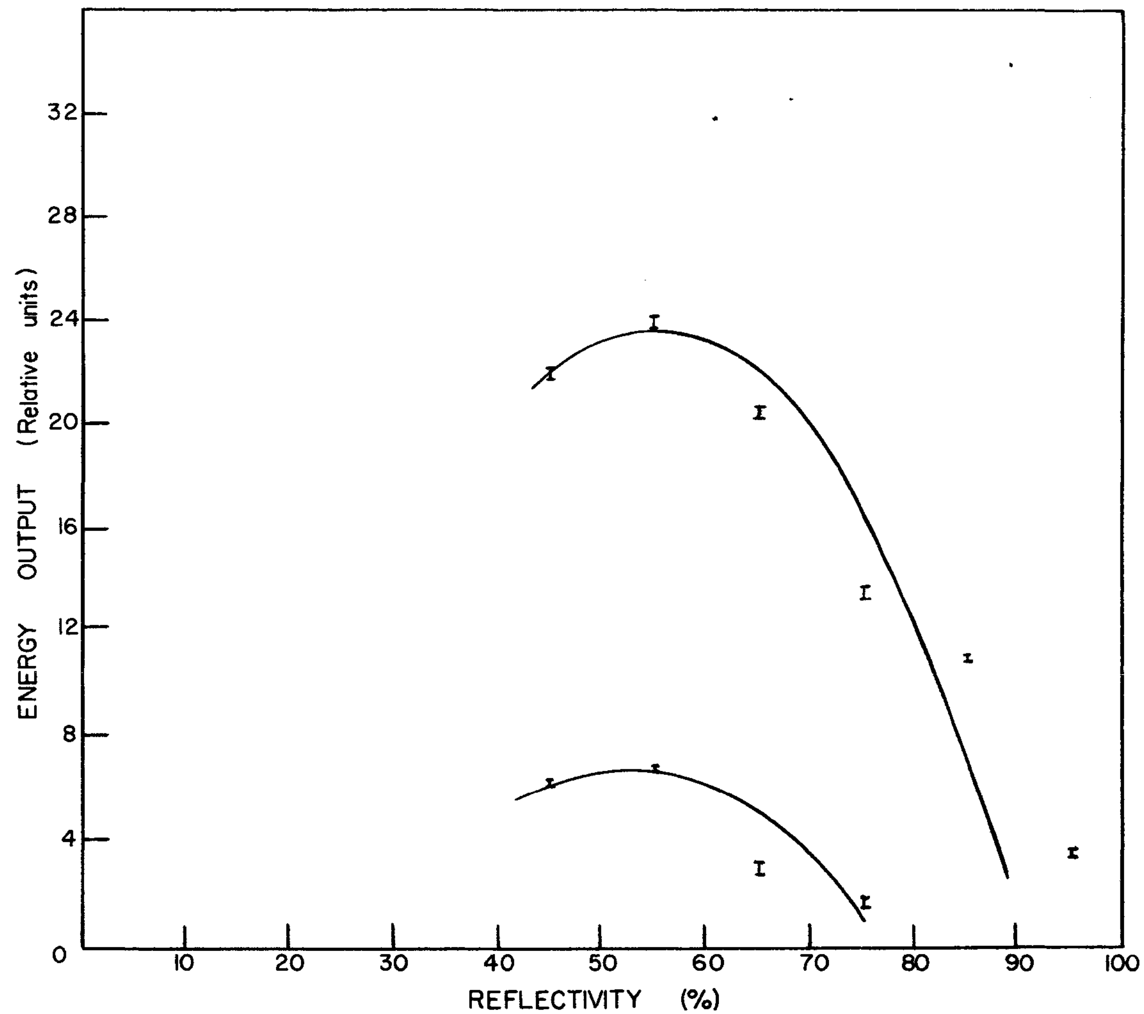

Fig.7. A graph of energy output against reflectivity with a cell containing only nitrobenzene in the cavity. Upper curve 3600 V input. Lower curve 3400 V input. (temp. setting 8.0 mV)

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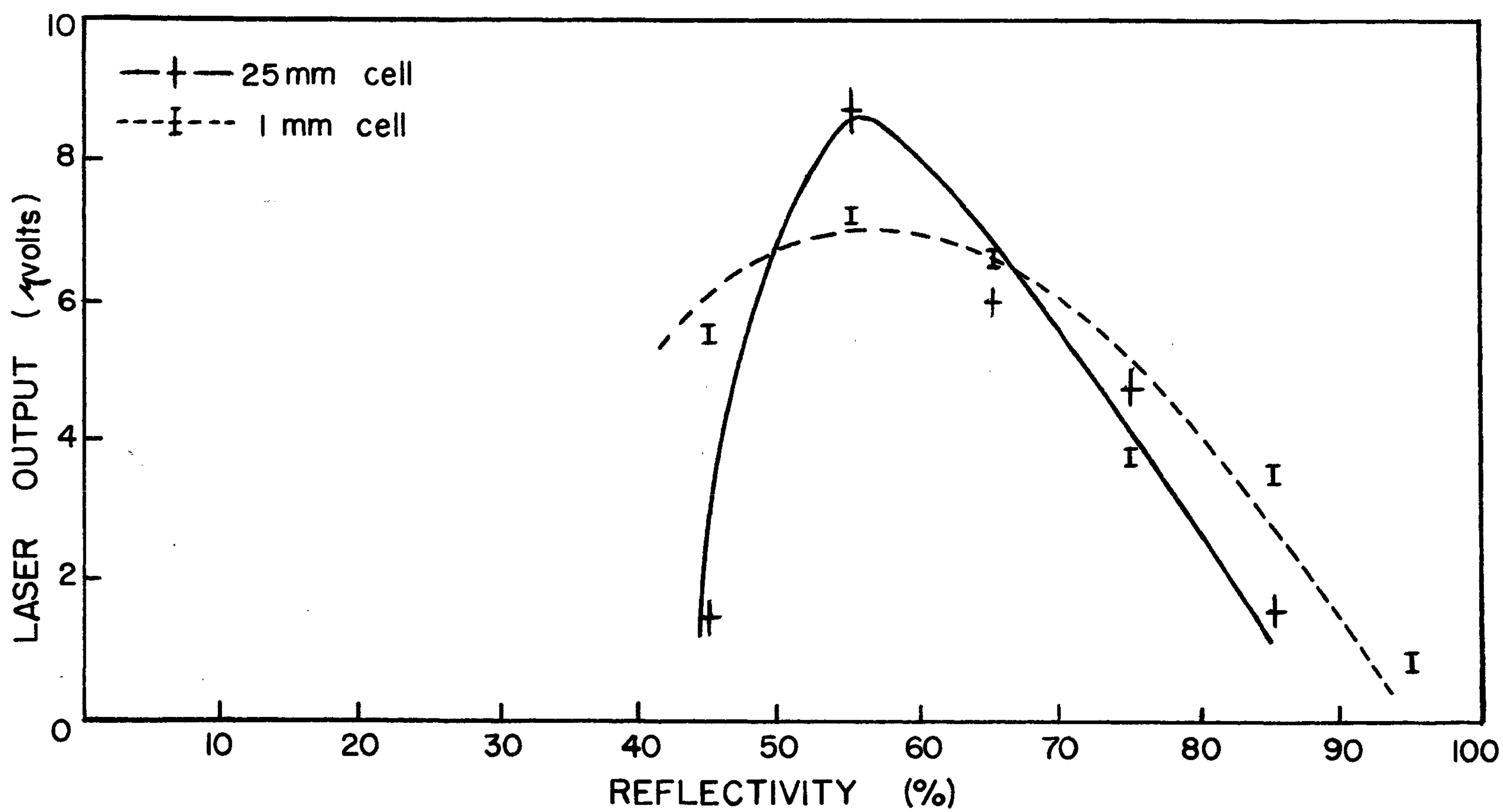

Fig.8. A plot of Q-switched laser output against mirror reflectivity for absorber cells of different path length. (pumping input 3400 V, temp. setting 8.3 mV)

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temperature corresponding to 8.3 mV. The absorber path length was taken into account by using a more concentrated dye solution in the shorter cell.

In examining the effects of absorber concentration on threshold, the results of which are given in Fig. 9, the concentration was increased past the point at which a single giant pulse was obtained in order to overcome the instabilities of the system. Measurements were made using a 10 mm cell and a solution of cryptocyanine with the ruby cooled to 114° K.

Fig. 10 shows normal laser oscillation just above threshold. Horizontal sweep is 0.5 msec/cm. Fig. 11 shows normal oscillation for the system pumped at 20% above threshold. Time base is 0.1 msec/cm. The oscilloscope trace of a typical giant pulse in Fig. 12 was obtained for phthalocyanine solution in a 25 mm cell with a 55% R end mirror while pumping the crystal at 27% above threshold (3600 VDC). Sweep speed is 0.1 μ sec/cm.

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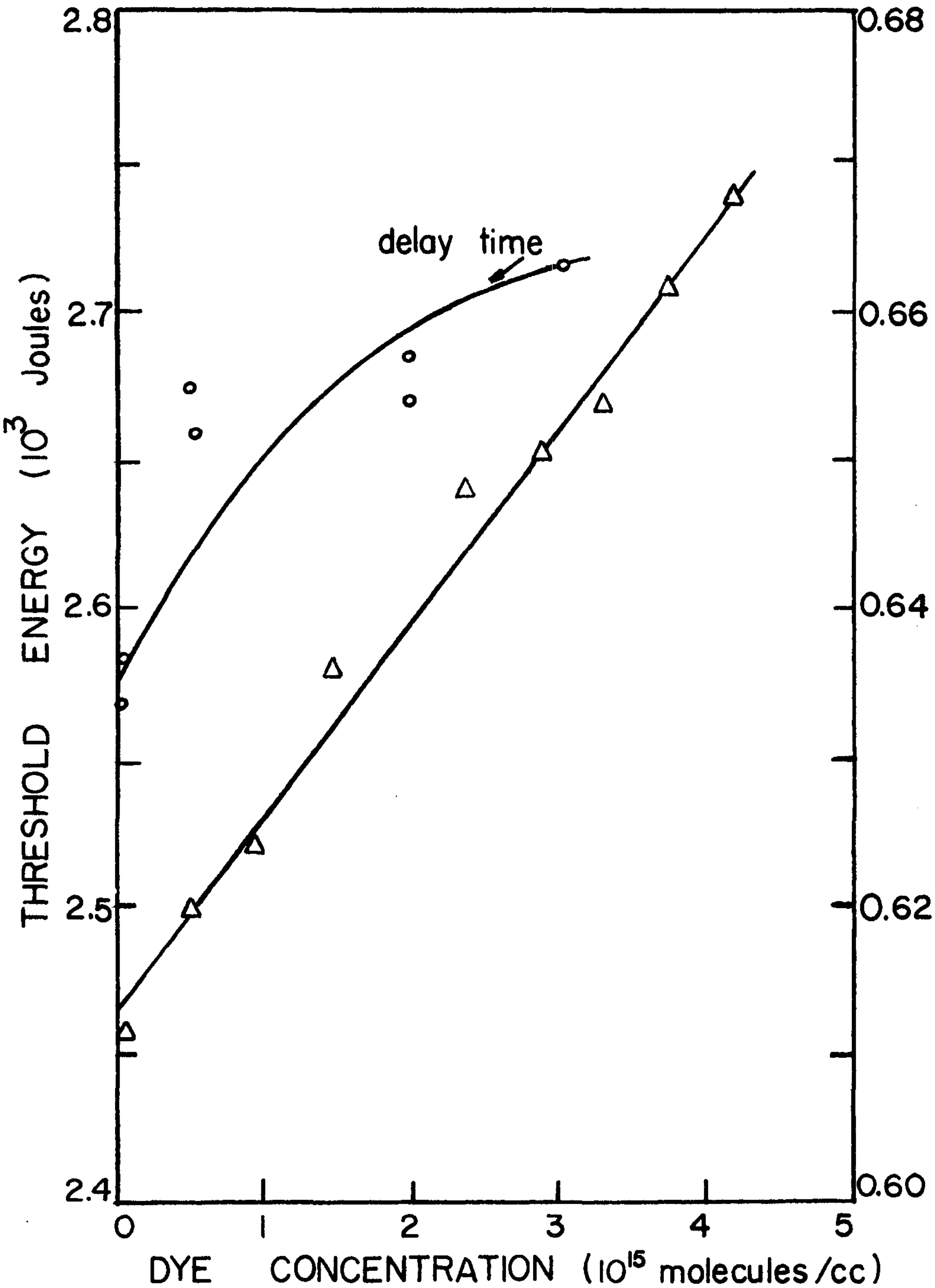

Fig.9. A plot of threshold energy and pulse delay time against dye concentration. (75%R cavity mirror, temp. setting 8.5 mV)

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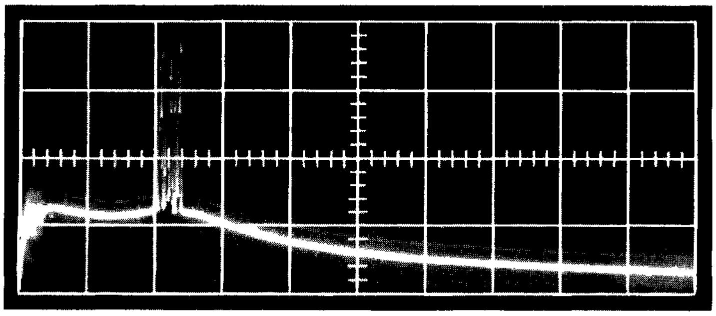

Fig.10. Normal laser oscillation just above threshold. Horizontal scale 0.5 msec/cm.

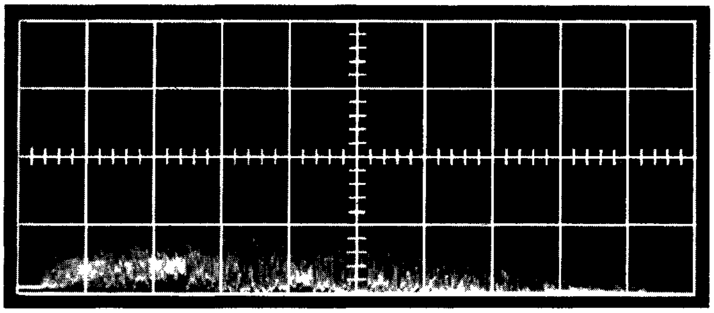

Fig.11. Normal oscillation for pumping input 20% above threshold. Time base 0.1 msec/cm.

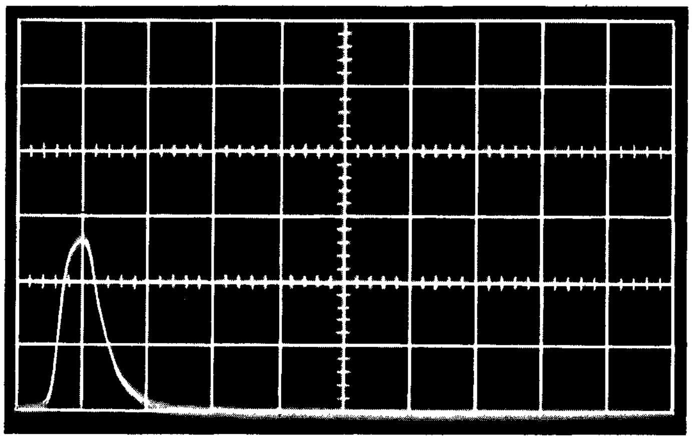

Fig.12. Typical Q-switched pulse for medium pumping of the ruby crystal. Time base 100 nsec/cm.

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VI. EVALUATION OF RESULTS

The increase in energy output as the temperature of the ruby crystal decreases, shown in Fig. 3, is directly related to the narrowing of the width of the R lines (cf. Fig. 13). The width of the R_1 line of a typical pink synthetic ruby changes from 21 cm^{-1} at 380° K to 0.3 cm^{-1} at 77° K[8]. As seen from equation (12) the increase in the number of non-oscillating modes made available for absorption of the pump energy as the temperature increases, decreases the value of the gain coefficient α at threshold. The peak value of α depends on temperature in the same manner as k_o, the absorption coefficient in unexcited ruby. Measured values of 0.4 cm^{-1} at 300° K and 10 cm^{-1} at 77° K have been obtained for k_o[9].

As cavity length increases, diffraction losses become more important in determining threshold. For small cavity dimensions, diffraction effects are negligible as can be seen from the following expression determined experimentally[10] for diffraction loss equivalent to that of dominant axial modes in a parallel mirror resonator:

$$\xi = 0.2\left(\frac{\pi\lambda L}{a}\right)^{1.45} \qquad (15)$$

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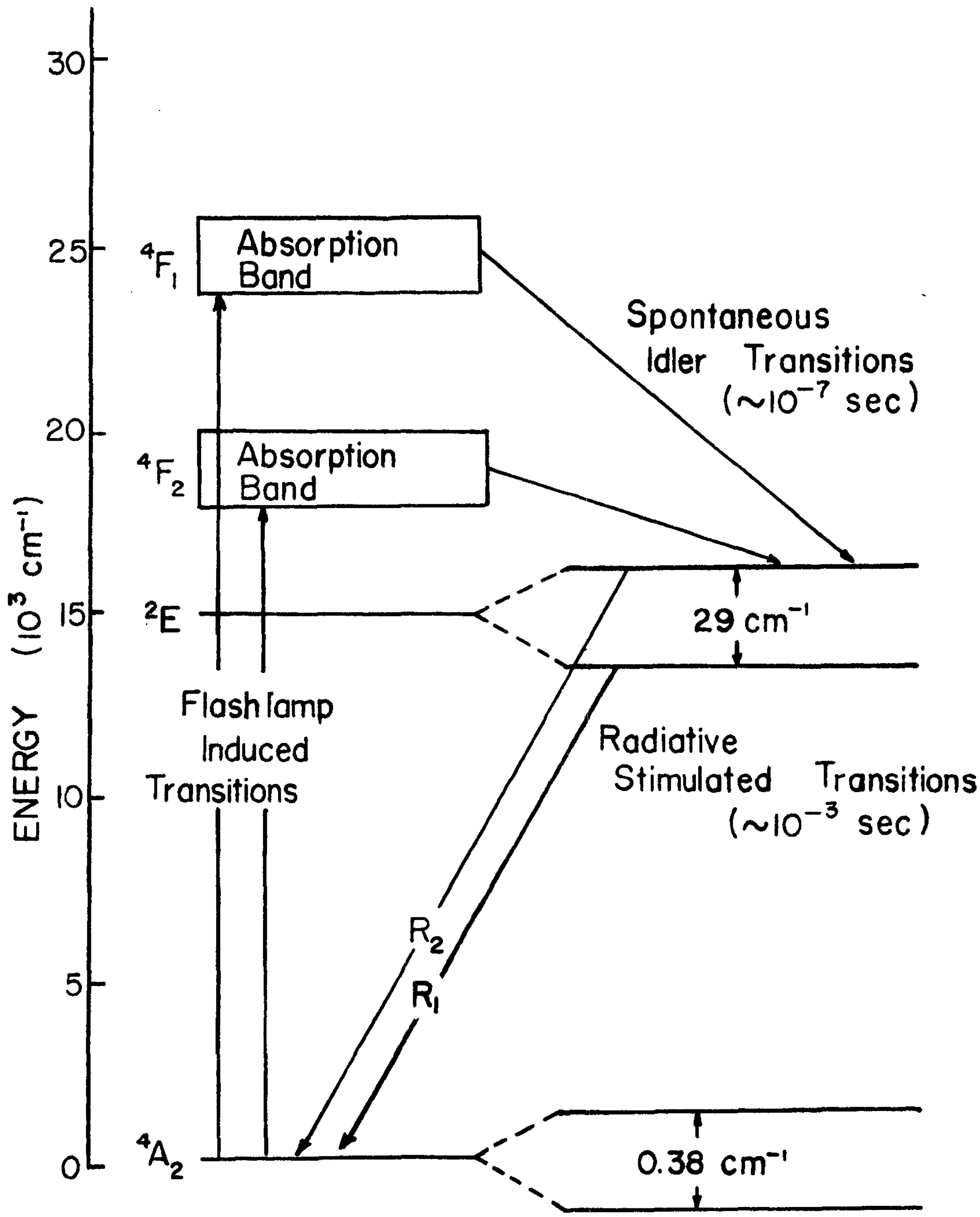

Fig.13. Energy level diagram for ruby

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where L is the cavity length and "a" the full aperture area of each mirror. Although ξ increases with L in the above expression, the values obtained for cavity dimensions given in Fig. 4 are still small compared with typical values of the transmission loss.

The diffraction loss for large L has been examined[11] under conditions that assume a far field effect characterized by initial lasing occuring only within a filament f of the rod's cross section. The condition for a far field diffraction effect is determined by the Fresnel relation $2L = f^2/\lambda$. The fractional loss by diffraction can then be expressed as unity minus the ratio of effective small aperture area to the area of the reflected beam at the laser rod,

$$\xi' = 1 - \left(\frac{f}{2L\Theta}\right)^2 \tag{16}$$

where $\Theta = \lambda/f$ is the beam angle bounding the radiation. For large cavity dimensions, values obtained for ξ' contribute significantly to the total cavity loss as compared to the case when L is small, hence causing the increased threshold observed in Fig. 4.

The characteristic instability of the laser system made comparative measurements of energy output as a function

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of reflectivity difficult to obtain. In figures 5 to 8 the reflectivity does not decrease below 35% since alignment of the external mirror was not optimized and with the expected increase in threshold energy in this region associated with a decrease in cavity Q due to radiation losses, valid measurements were not obtained.

Results indicate an optimum reflectivity for maximum output of approximately 55% in all cases. In Fig. 6 the optimum reflectivity changes only slowly with input energy in the practical operating range of the system. Considering the two extreme curves, a 27% increase in input energy results in a change in the optimum reflectivity from 65% to 55%.

An examination of the state of the laser system before and after Q-switching indicates that theoretically an absorber cell with 50% transmission per pass in a cavity with a 50% reflectivity end mirror would provide the best practical conditions for obtaining most of the peak power available. Below threshold, pumping of the Cr^{+3} ions from the ground state continues until the gain balances the losses associated with effective reflectivities of 1.0 and 0.125. After bleaching of the dye the reflectivities become 1.0 and 0.5. Hence, the ratio of actual initial inversion n_i to n_p, the inversion corresponding to threshold with absorber absent is approximately equal to 3, since from

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equation (6), the critical inversion varies as $\ln(1/\sqrt{R_1R_2})$ with the geometrical mean $\sqrt{R_1R_2}$ of the two end mirrors replacing the value for R, the reflectivity. Wagner and Lengyel[12] have plotted photon density versus time in the central region of a giant pulse for several values of n_i/n_p (n_i/n_p= 1.649, 2.718, 4.482, 7.389). The increase in peak power in going from the second value to the third which corresponds to a change from medium to high inversion is only a factor of about 2. Hence the ratio n_i/n_p= 3, which is approximately the largest obtainable with this system is great enough to provide most of the peak power theoretically available.

For the phthalocyanine solution in the 25 mm cell, pulse widths remained essentially constant for reflectivities between 95% and 55% but approximately doubled for reflectivities less than 55%. Cryptocyanine in a 1 mm cell yielded pulse widths which noticeably increased as reflectivity decreased, becoming approximately twice as wide for 65% R as for 95% R. This indicates that the width of the giant pulse is quite sensitive to the number of dye molecules per mm path length for a very short absorber cell.

The spread of the experimental points in Fig. 9 is due to the instability of the laser system. The results give a general indication of the increase in threshold for greater dye concentration caused by the increased losses

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(lower Q). Also, there is a detectable delay between the time that the pump is turned on and the time that the first pulse appears, since a longer time is required for the dye to reach a "bleached" state.

In summary, the Q-switched ruby laser meets the requirements for a source of intense radiation to study Thomson scattering as a plasma diagnostic tool. Theoretical considerations indicate that a 50% reflectivity end mirror used in conjunction with a 50% transmission absorber dye Q-switch and TIR ruby crystal give a value of approximately 3 for the ratio of initial inversion before Q-switching to inversion when the absorber is in the bleached state. Under these conditions most of the peak power is available as output. The sensitivity of the system to temperature, mirror alignment, cavity length, and pumping input made consistent determination of relative measurements very difficult. For the pulsed ruby laser system investigated, a 10-15 cm cavity length with the crystal cooled to 114° K (temperature setting 8.5 mV) provides the most practical conditions for maximum energy output at different input pumping levels. A power output of 1 MW has been obtained consistently at medium pump levels of 3080 J (3600 VDC). The energy contained in such a pulse with a 155 nsec width (cf. Fig. 12) is approximately 0.2 J. Harder pumping of the ruby is

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inconvenient for the repetitive firings required of the scattering technique since several minutes must elapse in each case to allow the laser system to stabilize. Greater output is, however, available from the present system since over 4 MW power has been obtained with an input of 3810 J (4000 VDC).

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