# Thermal Effect In Output Power of

# He-Ne 6328 Å Laser

by

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## 1. Introduction:

In operating He–Ne 6328Å laser with constant DC discharge power we can always find the output power increases for increasing of temperature of He–Ne mixed gas, decreases for decreasing of temperature of He–Ne mixed gas and a cut–off exists for a certain temperature.

Keeping the temperature of He–Ne mixed gas remains constant, the output power of the laser will change only with different values of discharge power. As the discharge power increases, the output power first reaches a maximum than falls down and also attains a cut–off.

It was discovered and originated by F. T. Arecchi in 1963 that the output power of a He–Ne laser is a function of temperature, discharge power and life times of transition levels. But his assumption: "Electron density in active medium is proportional linearly with discharge power." is not applicable in the abnormal glow region of gas discharge where laser action always occurs. Hence the expressions derived by Arecchi must be modified. This paper presents a theory of modification of Arecchi's expressions together with an experimental justification.

## 2. Output Power Equations:

In Section 2-1 we shall introduce a brief description and derivation of output power originated from Arecchi s paper (Reference 1). In Section 2-2 the output power equation is modified for practical conditions. In Section 2-3 the cut–off power is expressed as a function of temperature and decay rates.

## 2-1. Derivation of Output Power Equation

In the He–Ne discharge a resonant transfer of excitation transfer

occurs from the He (2'S) level to the Ne (3s$_2$) level, while the 6328Å laser action is observed on the 3s$_2$→2p$_4$ transition.

we shall denote by $\tau$ the whole spontaneous decay time from the 3s$_2$ state, by $\tau_{23}=1/\gamma_{23}$ the life time pertaining to the particular 3s$_2$→2p$_4$ transition (Fig. 1), by $\tau_a=\tau_{ao}\sqrt{\dfrac{T}{300}}$ the pumping rate, by p the density of e. m. modes within some linewidth $\Delta\nu_1$, by $\tau_B=\gamma_{34}\dfrac{\sqrt{T/300}}{a+\sqrt{T/300}}$ the effective depletion rate of the lower laser level where a$=\dfrac{\gamma_{43}}{\gamma_{41}^0}$ (Fig. 2,), and by T$_d$ the transit time between the mirrors times the reciprocal of the losses per pass. With reference to Fig. 1 let us call n$_1$, n$_2$, n$_3$ the populations per uuit volume in the levels 1, 2, 3; N the total Ne atoms density; $\rho$ the average density of photons at the laser frequency inside the e. m. cavity which is proportional to output power.

The coupled equations for the three levels of Fig. 1 and for the photon population will be

$$\frac{dn_2}{dt}=\frac{n_1}{\tau_a}-\frac{\rho}{p\tau_{23}}(n_2-n_3),-\frac{n_2}{\tau},$$

$$\frac{dn_3}{dt}=\frac{\rho}{p\tau_{23}}(n_2-n_3)+\frac{n_2}{\tau_{23}}-\frac{n_3}{\tau_B},$$

$$n_1+n_2+n_3=N,$$

$$\frac{d\rho}{dt}=-\frac{\rho}{T_d}+\frac{\rho}{p\tau_{23}}(n_2-n_3)+\frac{n_2}{p\tau_{23}},$$

It is useful to introduce the normalized power and square-root of temperature

$$y=\frac{P}{P_o},\quad x=\sqrt{\frac{T}{T_o}},$$

where the discharge power P$_o$=46 watts and the room temperature T$_o$=300°K.

The pumping rate $\gamma_a$ will be proportional to y through the fraction $\eta$ of He (2'S) atoms, and to x through the thermal velocity of the atoms

(1) $\gamma_a\varpropto\eta_o xy,$

where $\eta_o$ is the value of $\eta$ at P$_o$

$\gamma_{43}$ is the rate of exciation of the 2p$_4$ states by electrons' impact with

the Ne atom in the ls level. If we call $\sigma_{43}$ the cross-section for this process, $N_{el}$ the density of free electron in the discharge and v the electron velocity, it is easy to see that

$$\gamma_{43} \propto N_{el} v \sigma_{43}$$

If we assume that $N_{el}$ increase linearly with the discharge power then $\gamma_{43}$ will be proportional to the same power

(2) $$\gamma_{43} = \gamma_{43}^{\circ} y.$$

From the above considerations, $\gamma_\beta$ can be written as

(3) $$\gamma_\beta = \gamma_{34} \frac{x}{a_o y + x},$$

where

(4) $$a_o = \frac{\gamma_{34}^{\circ}}{\gamma_{41}^{\circ}},$$

is the ratio of the two rates at $x=1$, $y=1$.

The stationary value of $\rho$ is easily found beside some approximations that can be assumed in 6328Å He–Ne laser

(5) $$\rho = Cxy \frac{(\gamma_{34}/\gamma - 1/f)x - (a_o/f)y}{(\gamma_{34}/\gamma + (f-1)/f)x + [(f-1)/f]a_o y},$$

where C is constant, and

(6) $$f = \frac{\tau_{23}}{\tau}.$$

## 2-2. Modification of Output Power Equation

In the abnormal glow region (Reference 2) the discharge voltage increases with increasing current i. e., the plasma with positive "resistance". Our laser tube is operated in the linear region of the current vs voltage curve (Fig. 4) with positive "resistance" R.

The discharge current density can be written as

(7) $$i = N_{el} e v_d,$$

where $N_{el}$ is the electron density, e is the electron charge, $v_d$ is the average drift velocity of electron.

The average kinetic energy of one electron due to applied electric field can be written as

(8)
$$\frac{1}{2}mv_d^2 = AeV,$$

where V is the discharge voltage, m is the electron mass, A is proportional constant.

The discharge power is known as

(9)
$$P = iV = \frac{(V-V_o)^2}{R}.$$

Solving Equations (7), (8) and (9) for $N_{el}$

$$N_{el} \simeq [R^{-3/4}e^{-3/2}(\frac{m}{2A})^{1/2}]P^{1/4}.$$

Thus the electron density increases with $P^{1/4}$, but doesnot increase with P which assumed by Arecchi.

With the above arguments Equation (2) becomes

$$\gamma_{43} = \gamma_{43}{}^o y^{1/4}.$$

Equation (3) becomes

$$\gamma_\beta = \gamma_{43}\frac{x}{a_o y^{1/4} + x}.$$

Equation (1) remains correct otherwise we can not fit the theoretical values to the experimental curve of output power ve. discharge power at 300°K.

If $\gamma_\alpha \propto xy^{1/4}$ then Equation (5) becomes

$$\rho = Cxy^{1/4}\frac{(\gamma_{34}/\gamma - 1/f)x - (a_o/f)y^{1/4}}{[\gamma_{34}/\gamma - (f-1)/f]x + [(f-1)/f]a_o y^{1/4}}.$$

This curve, shown in Fig. 9 when f=1, its maximum can not be fitted to y=0.4 for any value of f.

If $\gamma_\alpha \propto xy^{1/2}$ then Equation (5) becomes

$$\rho = Cxy^{1/2}\frac{(\gamma_{34}/\gamma - 1/f)x - (a_o/f)y^{1/4}}{[\gamma_{34}/\gamma - (f-1)/f]x + [(f-1)/f]a_o y^{1/4}}.$$

This curve, shown in Fig. 9 when f=1, its maximum can not be fitted to y=0.4 for any value of f.

From above arguments we conclude that Equation (5) must be written as

(10) $$\rho = Cxy \frac{(\tau_{34}/\tau - 1/f)x - (a_o/f)y^{1/4}}{[\tau_{34}/\tau + (f-1)/f]x + [(f-1)/f]a_o y^{1/4}}.$$

In the normal glow region the discharge voltage remains constant for increasing discharge current such that

(11) $$P = Vi = constant \cdot i \ .$$

Solve Equations (7), (8) and (11) for $N_{el}$

$$N_{el} = [(eV)^{-3/2}(\frac{m}{2A})^{1/2}]P,$$

which is linearly proportional to P.

Equations (2), (3) and (5) remain correct in the normal glow region.

2-3. Cut-off Discharge Power Equation

From Equation (10) there are two discharge powers (or two y values), that exist at constant temperature (or constant x) for which $\rho = 0$, one is a trivial solution $y = 0$, another is

$$y = \left[\frac{1}{a_o}(\frac{f\tau_{34}}{\tau} - 1)\right]^4 x^4 \ or$$

(12) $$P = \left[\frac{1}{a_o}(\frac{f\tau_{34}}{\tau} - 1)\right]^4 \cdot (\frac{P_o}{T_o^2})T^2, \ or$$

(13) $$logP = 2 \ logT + log\left\{\left[\frac{1}{a_o}(\frac{f\tau_{34}}{\tau} - 1)\right]^4 (\frac{P_o}{T_o^2})\right\}.$$

From Equation (12) it is clear that cut-off discharge power is independent of distance between cavity mirrors and their reflectance. If $\frac{f\tau_{34}}{\tau} = 1$ or $\tau_{23} = \tau_{34}$ we have $\rho = 0$ for any value of x and y. We conclude that we can not achieve the population inversion for $\tau_{23} \leq \tau_{34}$ and thus we get $\rho = 0$ as it is expected.

3. Experimental Setup and procedure

The laser tube used in the experiment is filled with pure He-Ne mixed gas, He-Ne mixed gas pressure ratio is 7:1 and the total pressure is about 1 Torr. Length and the internal diameter of the tube are 35 cm and 0.2 cm respectively. The gas is discharged by a DC power supply. The resonant cavity is composed of two concave mirrors of reflectance 99%, radius of curvature 50 cm, which are arranged in parallel near the two ends of the discharge tube. The output power is measured with a

photomultiplier (Fig. 3).

The active region of the laser tube is wrapped by a doublelayer hollow cylinder. The inner layer is made of copper and the outer layer is made of plastic material, One end of the hollow cylinder is made free to move for avoiding the damage of the discharge tube caused by the thermal expansion or contraction of cylinder. Liquid air or cold air is introduced into the cylinder for lowering the temperature of the He–Ne mixed gas and maintain low temperature condition for experiment.

DC voltage is applied on the two ends of the laser tube and the He–Ne mixed gas is discharged. The discharging time duration is about 1–2 Seconds. The DC voltage is removed after taking the data of disch-arge power and output power. During this 1–2 seconds, the temperature of the He–Ne mixed gas doesnot vary significantly and can be regarded as a constant. We define this as "short time" discharge. The data obtained in the paper are all of "short time" discharge.

Actually the temperature of He–Ne mixed gas will rise a little higher after the "short time" discharge. But we may cool the laser tube for a long period of time until the laser tube reaches thermal equilibrium with its surrounding then the temperature of the He–Ne mixed gas will be identical to that of the surrounding and can be measured indirectly from the thermocouple which is coiled on the discharge tube. After these procedures, we are ready for another "short time" discharge.

Although care has been taken in order to diminish experimental errors, yet the thermal equilibrium between laser tube and its surrounding is difficult to attain, and the temperature of the He–Ne mixed gas can not be measured exactly.

4. Experimental Results and Discussions

The current voltage relation of our laser tube is first investigated, the result is shown in Fig. 4. It is obvious from the result that it is operated in so called abnormal glow region of a plasma discharge.

4–1. Cut–off Temperature and Cut–off Discharge Power

In order to prove the cut–off temperature for constant discharge power is independent of resonant modes, distance between cavity mirrors and mirror reflectance, we can change the resonant modes, distance

between cavity mirrors (Fig. 5) and reflectance of mirrors (Fig. 6), the result is that cut-off temperature varies within 20°C and it is acceptable as a constant within the experimental errors.

The curve of cut-off discharge power vs. cut-off temperature is plotted in Fig. 7. From experimental results, its tangent slope is 2 the same as that of Equation (13). Thus our modification of output power equation obtained by assuming $N_{el} \propto P^{1/4}$ instead of $N_{el} \propto P$ is justified. The experimental errors are large for low cut-off temperature and small cut-off discharge power, so that the experimental points are remote from curve for this case.

4-2. Output Power and Discharge Power at Constant Temperature.

We keep temperature constant at 185°K, 217°K, 273°K and 300°K, to investigate the relation between discharge power and output power respectively. The results are indicated in Fig. 8 and the following conclusions can be obtained from the experimental results:

(1). Shape of the output power vs. discharge power curves are similar for different temperatures.

(2). For the same discharge power the higher temperature implies the higher output power, that is clearified in Fig. 5 and Fig. 6 also.

(3). For different temperature, there exists an optimum discharge power for maximum power output.

The reality of above conclusions are expected from Equation (10).

4-3. Estimation of Transition Life Times

Transition life times $\tau$ and $\tau_{23}$ can not be calculated (Reference 3), if one of these is known the other can be estimated by the method indicated below:

Since in Equation (10)

$$r_{34} \simeq 8.10^7 \text{ sec}^{-1}, \qquad \text{(Reference 4)}$$

$$x = 1, \qquad \text{(for } T = 300°K)$$

$$\rho = 0, \qquad \text{(for } y = 1)$$

and we may assume

$$r \simeq 10^7 \text{ sec}^{-1}, \qquad \text{(Reference 1)}$$

implies;

(14) $\qquad a_o \simeq 8f-1$

Substitute Equation (14) into Equation (10) and solve for f by setting the maximum of $\rho$ at y=0.4 (Fig. 9) thus

(15) $\qquad f \simeq 1.4$

Substitute Equation (15) into Equation (14) thus we have

$$a_o \simeq 10,$$

by using Equation (6) we have

$$\tau_{23} = f\ \tau = 1.4 \cdot 10^{-7}\ \text{sec,}$$

Since $\qquad \tau_{41}^{\circ} \simeq 2 \cdot 10^5\ \text{sec}^{-1}$, $\qquad\qquad\qquad$ (Reference 1)

and by using Equation (4) we have

$$\tau_{43}^{\circ} \simeq 2 \cdot 10^6\ \text{sec}^{-1},\ \text{or}$$

$$\tau_{43}^{\circ} \simeq 5 \cdot 10^{-7}\ \text{sec,}$$

## 5. Conclusions

The argument just presented shows that modified output power equation fits the experiments, and from experimental results we conclude that:

(1). Laser tube is operated in abnormal glow region with electron density proportional to one fourth power of discharge power.

(2). For constant discharge power, the output power increases as the temperature goes up, that is because of an increasing in the quenching rate of the metastable level of Ne (ls) and in the pumping rate of the Ne ground level.

(3). For constant discharge power the cut–off temperature is indepen-dent of cavity length, reflectance of mirrors and resonant modes.

(4). As the temperature goes up, the cut–off discharge power increases.

(5). At constant temperature the output power goes to zero after reac-hing a maximum. The output power increases as the discharge power increases, because of an increasing in pumping rate of ground level of Ne. After reached a maximum the depletion rate of the metastable level of Ne ($2p_4$) decreases and the excitation rate of the metastable level of Ne (Is) increases more rapidly

such that the accumulation of electrons in Ne (2p₄) level makes the population inversion break down, and the output power goes to zero.

Reference

1. F. T. Arecchi, Proceedings of The Third Quantum Electrons Conference (Paris, Feb. 11–15, 1963).
2. A. von Engle, Ionized Gases, Chapter 8, Oxford England, 1955.
3. W. R. Bennett, App. Opt., 1962, supp. 1. pp. 44.
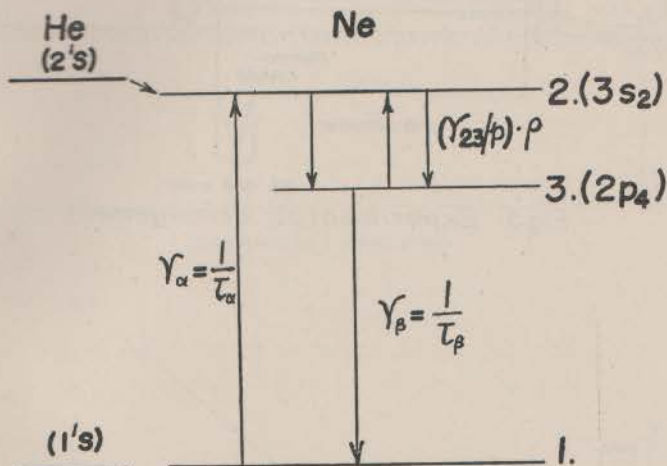4. W. R. Bennett, Phys. Rev., 126, 588 (1961).
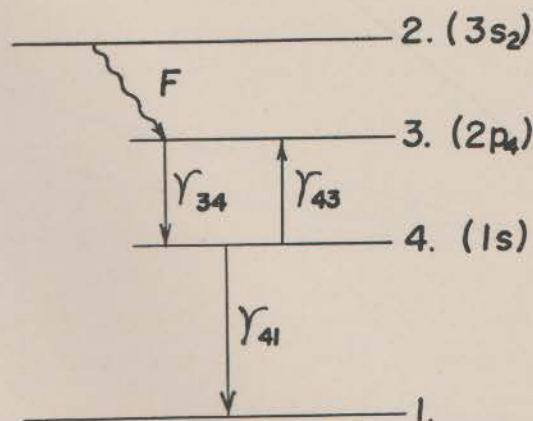
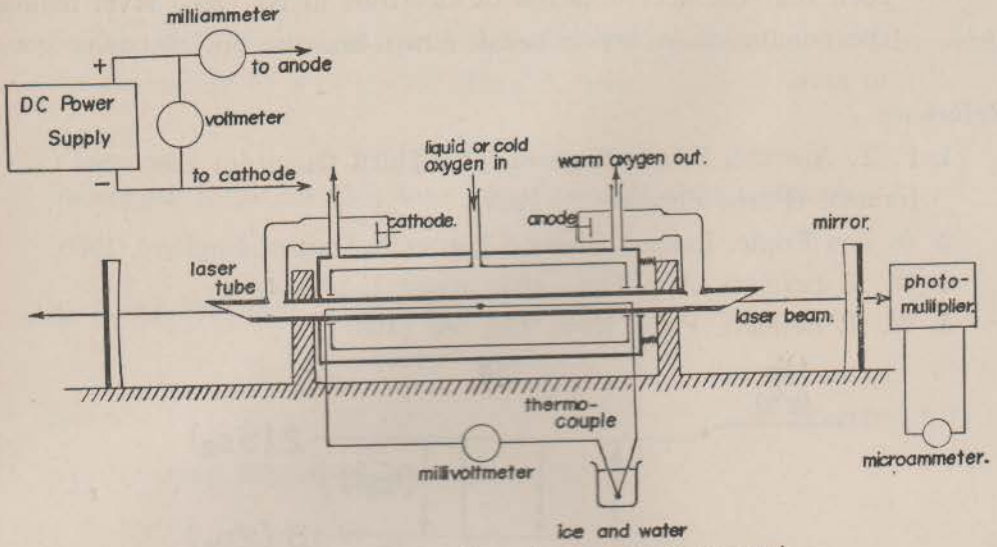Fig.I. Simplified three level diagram of the laser action.

Fig.2. Four-ievel diagram of the laser action.

Fig.3. Experimental arrangement.
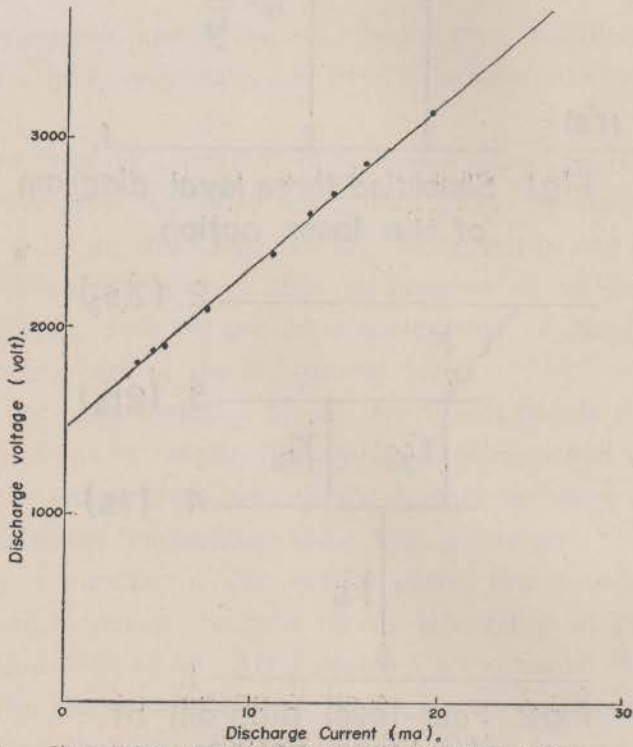


Fig. 4. Discharge voltage vs. discharge current of laser tube.

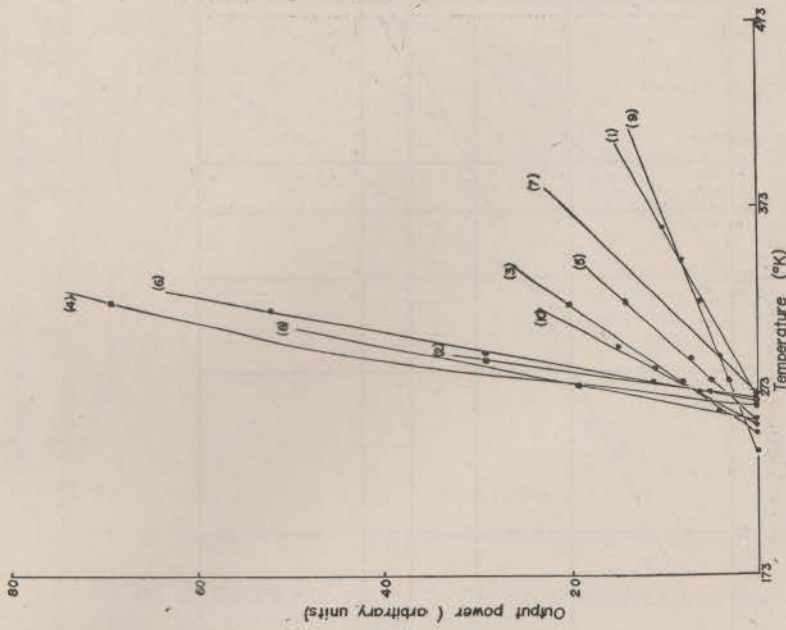Fig.5. Output power vs. temperature for different cavity length (with 32 watts discharge power) corresponding to:
(1).41.5 cm,TEM$_\infty$ mode. (2).41.5 cm,TEM multimode. (3).50 cm,TEM$_\infty$ mode. (4).50 cm,TEM multimode. (5).60 cm,TEM$_\infty$ mode. (6).60 cm,TEM multimode. (7).80 cm,TEM$_\infty$ mode. (8).80 cm,TEM multimode. (9).90 cm TEM$_\infty$ mode. (10).90 cm,TEM multimode.



Fig.6. Output power vs. temperature for different reflectance of mirror (with 32 watts discharge power, 50 cm cavity length).
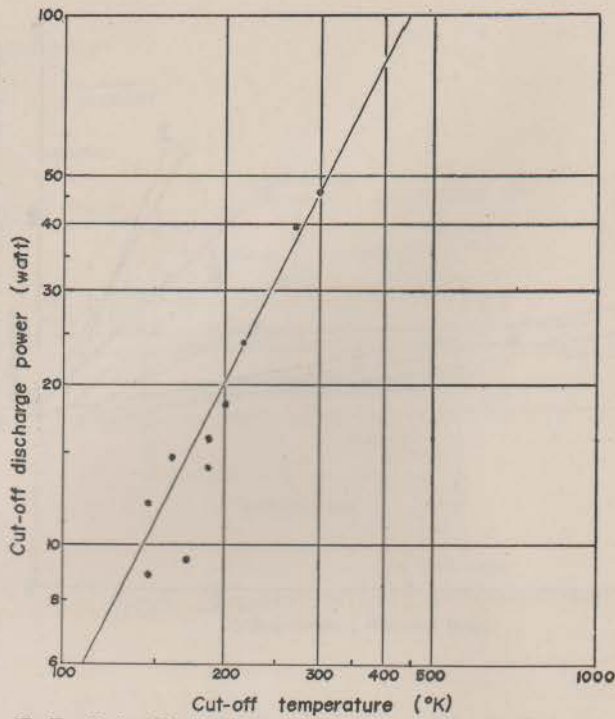corresponding to: (1) 99% reflectance. (2) 98% reflectance.

Fig.7. Cut-off discharge power vs. cut-off discharge temperature
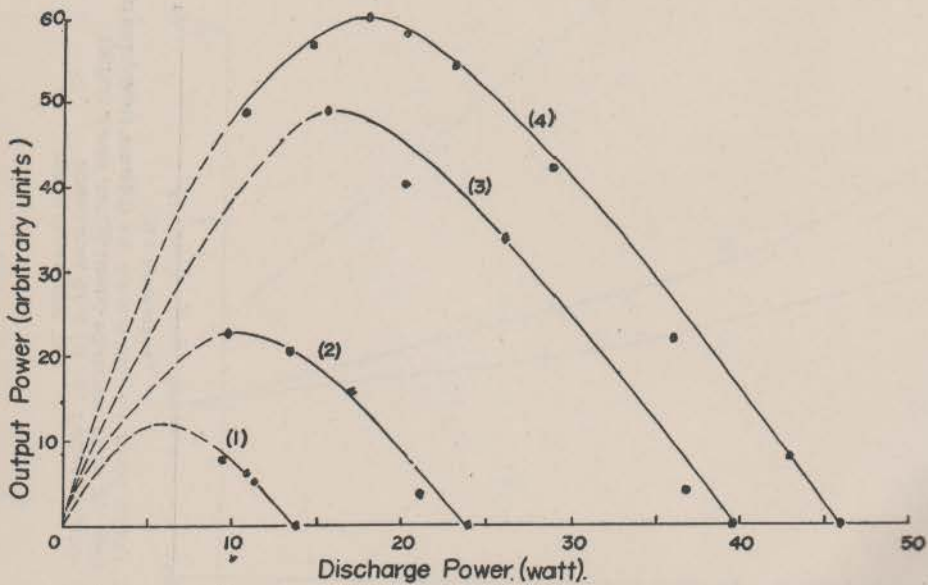


Fig.8. "Short time" behaviour of the laser output power vs. discharge power at equilibrium temperature corresponding to:
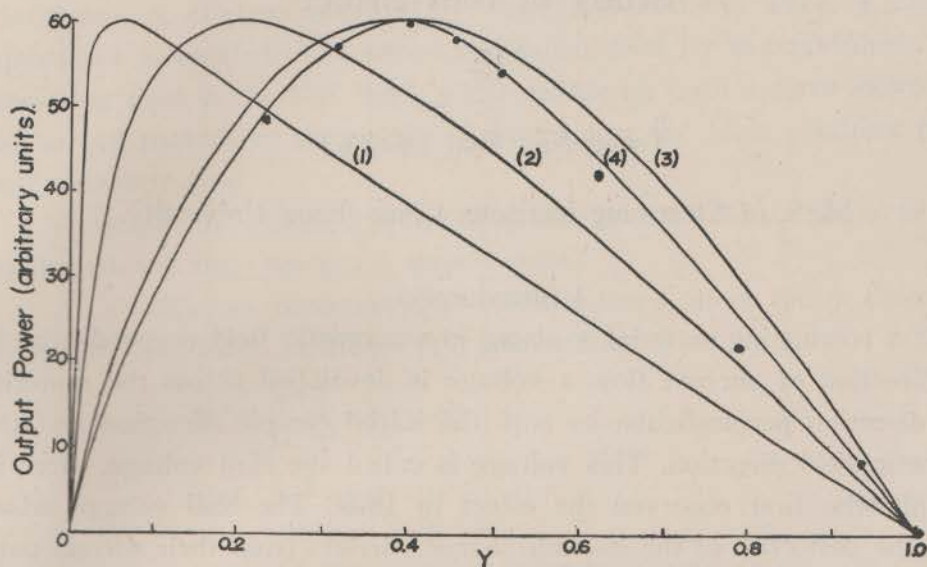(1). T=185°K.  (2). T=217°K.  (3). T=273°K.  (4). T=300°K.

Fig.9. Fitting of theoretical values to the experimental curve for output power vs. discharge power at $300°K$.
(1) theoretical plot when $Y_a \propto \eta_o xy^{\frac{1}{4}}$ (2) theoretical plot when $Y_a \propto \eta_o xy^{\frac{1}{2}}$
(3) theoretical plot when $Y_a \propto \eta_o xy$ and $f=14$ (4) experimental plot.