

縱向激發二氧化碳雷射之特殊激勵法

A Novel Excitation Scheme for Longitudinal-Excited Carbon Dioxide Lasers

黃廣志 Kuang-Chih Huang

Department of Electrophysics

許根玉 Keng-Yu Hsu

Institute of Electronics

(Received January 14, 1976)

ABSTRACT — A new approach, based on a double-pulse-discharge technique, has been successfully performed on a LE CO₂ laser.

This technique consists of two consecutive discharges. First, the preionization discharge, which is higher in voltage and less energetic. Then, after some delay time, the main discharge follows.

TEA laser can perform double-discharge effectively, but it requires auxiliary preionization-electrodes. Double-discharge technique has been only possible for multi-electrode lasers [1].

Now, the new technique developed by us has been demonstrated to be capable of solving the above-mentioned difficulty beneficially.

The discharge circuit is mainly constructed by using capacitors and spark gaps, and is ready to apply to any two-terminal discharge tube.

Comparisons between this device and the same discharge tube [4,5] using conventional excitation technique show that the laser energy and overall efficiency can be increased at least by a factor of 1.5, and the optimal E/P ratio was decreased. Furthermore, the improved discharge conditions also enable arcing-free operation with higher pressure than that of applying conventional discharge technique.

Up to the present time, this is the only preionization technique for the LE CO₂ laser.

1. Introduction

The CO₂ gas laser has a number of advantages over solid-state lasers. Among which the most important are the followings:

(1) CO₂ laser has much higher efficiency

The efficiencies of solid-state lasers are usually less than one percent. Whereas for CO₂ laser, it might reach as high as 10 to 30 percent.

(2) CO₂ laser has simpler cooling problems

For CW high power CO₂ lasers, water-jacketed cooling is enough, while for general pulsed operation no special cooling is required. But for solid-state lasers, the most difficult one comes out of the cooling problem. For instance, at the threshold of a ruby laser, the rate of energy that must be absorbed by the ruby rod is about 1.27 KW/cm³. The optical pumping system must be designed so that the heat developed can be removed fast enough to prevent any intolerable rise of temperature in any component.

(3) CO₂ laser is very much economical

The solid-state laser usually requires an optically perfect crystal, these rods are relatively expensive than gases. CO₂ lasers need no crystals, therefore they could be much cheaper.

(4) CO₂ laser has larger average power

The peak power of a Nd: Glass laser can be as high as 10¹² watts, but the pulse energy is only around 10 J, and the repetition rates are also very low (less than 1 PPS). The largest average power from solid-state lasers could be, by the time being, obtained from the Nd: YAG laser. Its value is about 250 watts. Looking at the CO₂ laser, however, it can offer continuous output of the order of kilowatts easily. It can be operated in high repetition rate in the range from 100 to 1000 PPS. When in pulsed operation the optical output energy can reach hundreds of joules with peak power in the multigigawatt range. More important is the great potential of technical improvements. It therefore attracts most efforts of the current research.

1. Research Objectives

From the economical principle point of view, we need a high efficiency laser system.

The objective of this thesis is to investigate a new excitation technique to improve the efficiency of LE CO₂ lasers. LE CO₂ lasers have some advantages over TE lasers. TE lasers require at least three electrodes, two for main discharge and the others for preionization discharge. Whereas LE lasers need only two electrodes. On the other hand, the cathode of a TE laser must be shaped in such a way that the uniform field profile (usually Rogowski or Bruce profile) could provide a large discharge area. This requires some precise technology and makes costs high. Whereas the Electrodes for LE lasers have simpler structure, and hence, it makes the whole

system more economical.

2. Organization of the paper

The organization of this paper is subdivided into seven sections. Following the section one, introduction, the second section covers some of the important characteristics of CO_2 laser plasma and gives the principles toward high power lasers. The third section describes the new double-pulse-discharge technique discharge for LE CO_2 lasers. This section constitutes the most important feature of this paper. Section four describes the experimental apparatus and the measurement technique. The experimental results and discussions are then presented in section five. Section six gives a summary of conclusions. Some of the recommendations for further study will be presented in the last section.

II. Investigations of High Power CO_2 Lasers

1. Properties of CO_2 Laser Plasma [2,3]

There exists no universal agreement on the model of the kinetics of the detail physical processes of CO_2 lasers. The difficulty arises because of the inherent complexity of CO_2 laser plasma. Beside the collisions between electrons, CO_2 , N_2 and He molecules, there are many plasma-generated impurities. These impurities may be in the form of neutral, such as CO, O, N, NO, O_2 and NO_2 , or positive ionic species, such as CO_2^+ , O_2^+ and NO^+ , or negative ionic species, such as CO_3^- , NO_2^- , O_2^- and NO_3^- etc.

The experimental results showed that these changes of gas mixture can significantly affect the performance of CO_2 lasers. The most important one is the formation of CO and O at the expense of CO_2 molecules. These molecules (especially CO) compete with CO_2 and N_2 for electron energy and therefore constitute serious energy loss channels. Furthermore, the concentrations of some negative ions such as CO_3^- and NO_2^- may be comparable to or significantly greater than the electron density. These quantities may contribute the onset of discharge instabilities which reduce discharge power density seriously.

According to Nighan's analysis [6], the most important energy transfer process influencing vibrational populations in CO_2 laser plasmas are the following: (Fig. 1)

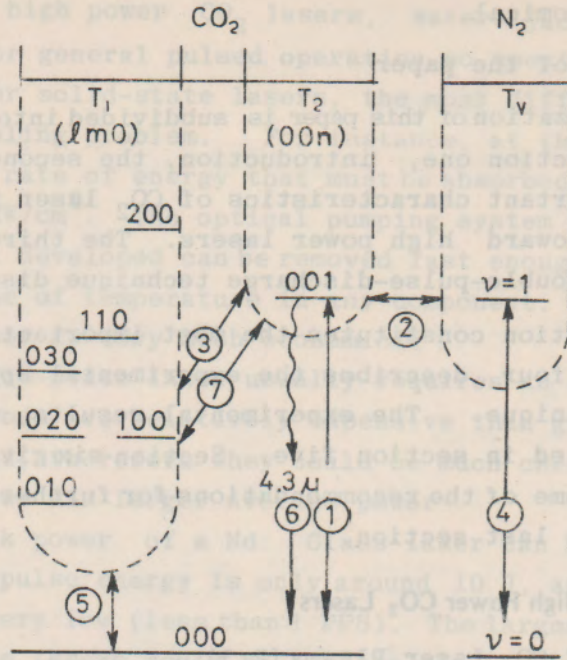


Fig. 1 Important processes in CO₂ lasers.

(1) electron excitation of the CO₂ asymmetric stretch mode, (2) vibrational energy exchange between N₂ and the CO₂ asymmetric stretch vibration, (3) excitation (and deexcitation) by atoms and molecules of the CO₂ asymmetric stretch vibration from the coupled bending and asymmetric stretch system, (4) electron vibrational excitation and deexcitation of N₂, (5) electron and heavy particle excitation and deexcitation of the coupled CO₂ symmetric stretch and bending vibrations, (6) spontaneous emission of 4.3 μm radiation, and (7) stimulated emission and absorption of radiation with wavelength of 10.6 μm.

Among these seven the dominant process responsible for population inversion between CO₂ (00⁰1) and (10⁰0) level is the direct electron impact excitation (1).

The calculation of rate constant for each process combining with the electron energy distribution function permitted evaluation of many important parameters of CO₂ lasers as small signal gain, saturation intensity, optical power density and overall laser efficiency for a variety of performance conditions. This provides us as a guide to achieve high efficiency, high power CO₂ lasers, which is

just the subject under current research.

2. High Efficiency High Power CO₂ Lasers

From the above analysis we can qualitatively catch the principles for high efficiency high power CO₂ lasers. They are:

(1) Raising the gas pressure. This provides more active molecules per unit volume.

(2) Maintenance of stable glow discharge at high pressure and high electrical current density. This would increase fractional power transfer to upper laser level of CO₂ molecules.

(3) Maintaining low gas temperature. This prevents the populating of the lower laser level of CO₂ molecules, thus maintaining the small signal gain.

(4) Using fast gas flow. The discharge-induced impurities may be carried away, and the problem of overheating will be effectively solved.

Unfortunately, the principles of (1) and (2) become more difficult as the pressure is increased. The difficulty results from two effects:

(1) Higher pressure requires higher voltage to discharge with a given electrode construction.

(2) The probability of occurring discharge instability increases and the gas will be easily brought into a bright arc hence laser energy degrades rapidly.

The change of discharge path from longitudinal direction (LE) to transverse direction (TE) bypassed the first difficulty rather effectively.

The second problem has been solved by the use of double-discharge technique, by UV photo-preionization, or by e-beam controlled discharge. The results are fruitful and being under further developments. All these schemes are more complicated than LE lasers. The development of the new double-pulse-discharge technique for a LE CO₂ laser presented in this thesis makes the construction more simple and achieves high efficiency.

III. Description of the New Excitation Technique

It is not easy to control the time delay between two multi-kilovolt pulses in the submicrosecond range, especially for the discharges between the same electrodes. That's the reason why double-discharge LE CO₂ lasers have never been reported.

The technique consists of two consecutive discharges: The first is a high voltage, less energetic preionization discharge, and the second is a lower voltage, more energetic main discharge.

The discharge circuit is shown in Fig. 2. The 250 pF capacitor C_p provides the required energy for preionization discharge. This discharge ionizes a small fraction of molecules. Since the glow to arc transition requires finite time to occur, the small capacitance of C_p keeps a very short time constant thus prevents the discharge from arcing. At the same time, diffusions and collisions of the ions, molecules and electrons will make the laser plasma more uniform in the whole volume, and the gas is left somewhat excited.

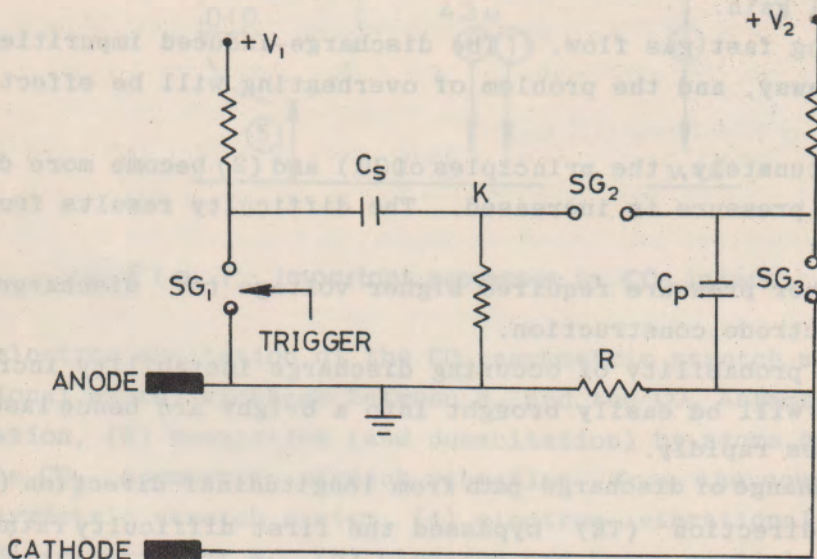


Fig. 2 Schematic of double-discharge excitation circuit

C_s — Energy storage capacitor, 0.02 μF

C_p — Preionization capacitor, 250 PF

SG_1, SG_2, SG_3 — Controlled spark gaps.

In some appropriate later time, the spark gap SG_3 fires and main discharge starts. This discharge has the characteristics of low discharge field strength and high current density. The energy stored in C_s may pass rapidly through the gases below breakdown voltage where arcing doesn't occur.

This fast injection of large energy facilitates the generation

of a high peak power laser pulse. Furthermore, since the energy spent in the preionization discharge is much less than 1% of the total energy, this technique permits a high efficiency operation of CO₂ laser.

Let's summarize the sequence of events as follows:

(1) Once the spark gap SG₁ was triggered by an external trigger source, the spark gap SG₂ fires immediately. Then preionization occurs.

(2) After an optimal degree of preionization, the spark gap SG₃ fires automatically. The energy stored in C_S initiates and sustains the main discharge. Laser pulse then results.

IV. Experimental Apparatus

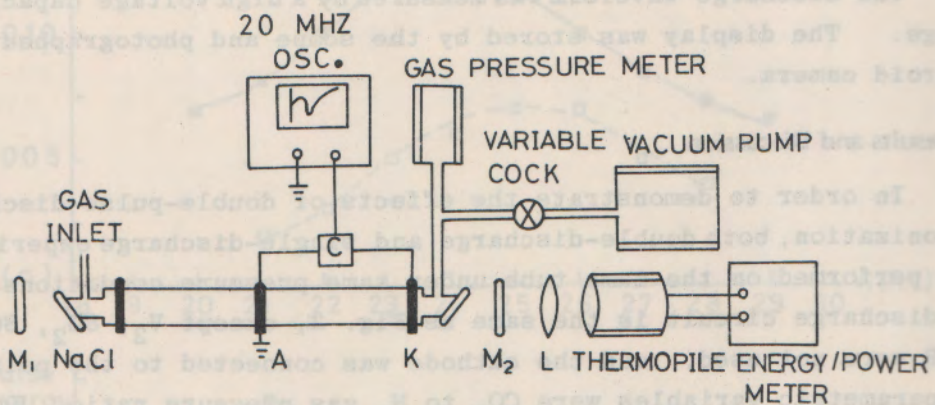


Fig. 3 Block diagram of the experimental set-up

M₁ - 100% Reflector, Radius of curvature = 10m

M₂ - 50% Reflector, Radius of Curvature = 10m

L - Focussing Lens

K - Cathode

A - Anode

C - 1 : 40000 capacitor bridge

The block diagram of the experimental set-up is shown in Fig. 3. The laser cavity has a total length of 165 cm. The discharge tube is a 150 cm-long 35 mm-bore pyrex tube. Due to the insufficient dimensions of NaCl crystal, the two ends of the tube were connected to a 25 mm-bore tube.

A gold coated mirror with 2mm-hole at the center and 10m radius of curvature was used as 100% reflector. The energy loss from the small hole was assumed to be negligible. The 2mm-hole was used to align the optical cavity with a He-Ne laser.

The output mirror was a Ge 50% partial reflector.

The discharge tube has a two-module construction with common anode grounded at the center. The total discharge length is 140 cm, and NaCl windows were cut at the Brewster angle.

The partial pressure of each kind of gas was controlled by a flow meter. The total pressure was read from a mercury meter.

A germanium focussing lens with 25 cm focus length was used to focus the output laser beam. The output energy was measured by a HADRON/energy/power meter.

The discharge waveform was measured by a high voltage capacitor bridge. The display was stored by the scope and photographed by a Polaroid camera.

V. Results and Discussion

In order to demonstrate the effects of double-pulse-discharge preionization, both double-discharge and single-discharge experiments were performed on the same tube under same pressure conditions. Single-discharge circuit is the same as Fig. 2, except V₂, SG₂, SG₃, C_p and R were not used, and the cathode was connected to the point K. The parametric variables were CO₂ to N₂ gas pressure ratio, He partial pressure, repetition rates, C_p and C_s. The reported value for each point was averaged over three measurements.

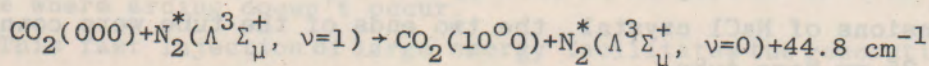
1. CO₂ : N₂ pressure ratio dependence

The result was shown in Fig. 4, where the helium pressure was kept at 18 torr and the CO₂ : N₂ ratio was varied from 1:1, 2:1, to 3.5:1.

The effect of N₂ in CO₂ lasers is to help increasing the population of upper laser level (00⁰1) by vibrational energy transfer:

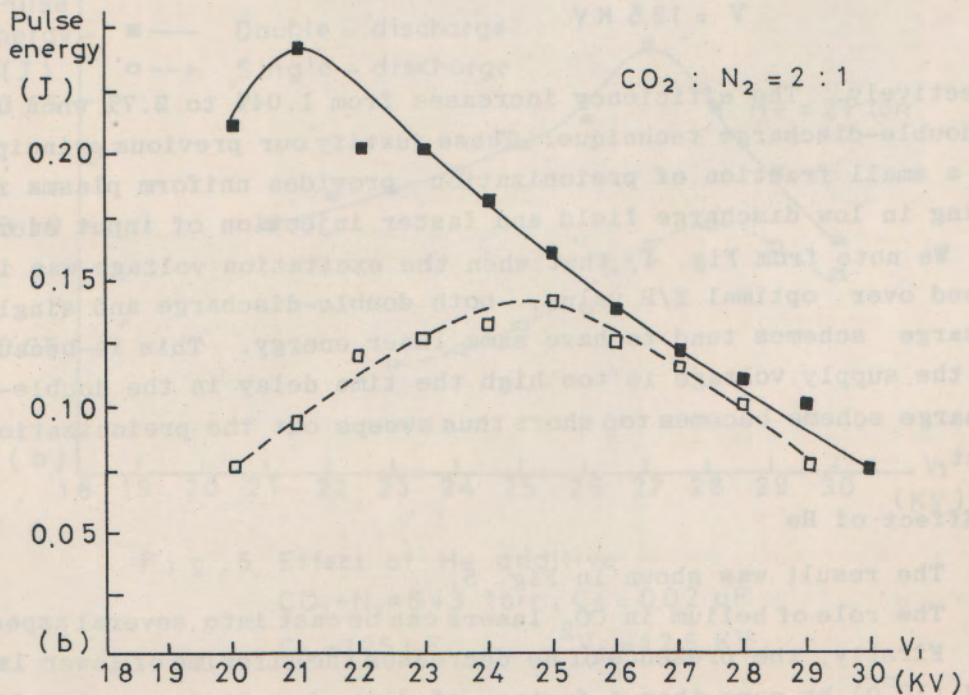
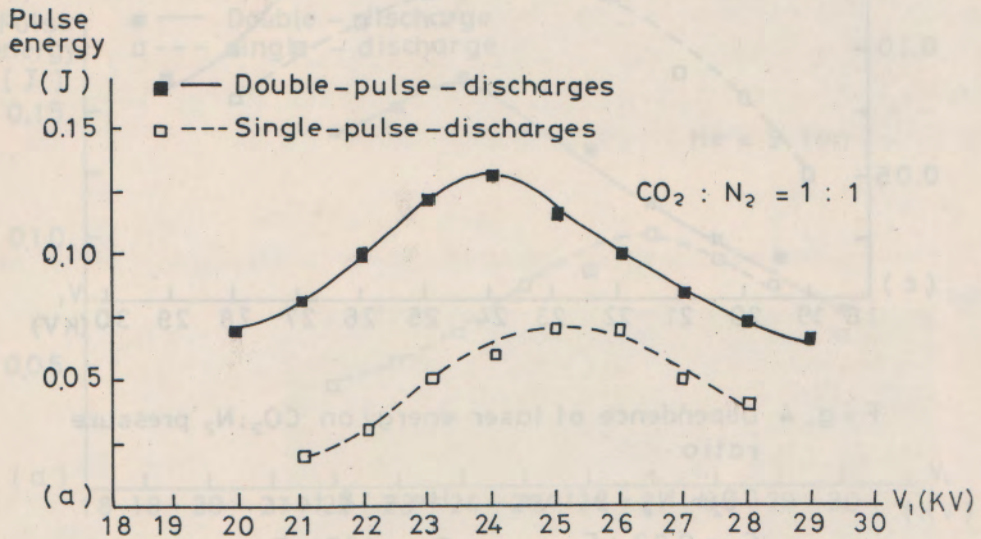
CO₂(000)+N₂(v=1) → CO₂(00⁰1)+N₂(v=0)-18 cm⁻¹, hence, addition of N₂ can raise the output power as seen in Fig. 4(b) and 4(c).

On the other hand, N₂ also increases the lifetime of CO₂ (10⁰0) level by the energy transfer:



at the same time, N_2 molecules deplete the CO concentration, whereas CO can deexcite $CO_2(10^0_0)$ level very effectively. Thus if there exists too much N_2 molecules, the relaxation of lower laser level becomes less efficient, and the discharge impedance increases. The laser power thus decreases as seen in Fig. 4(a).

By comparisons in Fig.(4), the maximum pulse energy from double-discharge laser is 0.24J, and the optical E/P ratio is 12V/cm-torr. For a single-discharge device they are 0.14 J and 14 v/cm-torr,



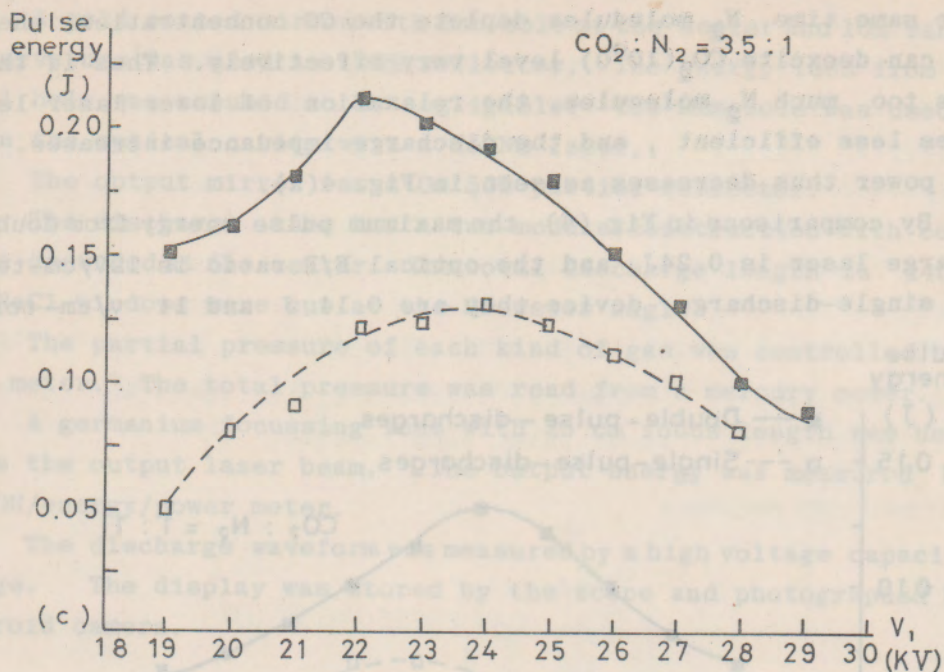


Fig. 4 Dependence of laser energy on CO₂:N₂ pressure ratio.

CO₂ + N₂ = 9 torr He = 18 torr.

C₁ = 0.02 μF C_p = 125 pF

V = 12.5 KV

respectively. The efficiency increases from 1.04% to 2.7% when using double-discharge technique. These justify our previous principles that a small fraction of preionization provides uniform plasma resulting in low discharge field and faster injection of input energy.

We note from Fig. 4, that when the excitation voltage was increased over optimal E/P value, both double-discharge and single-discharge schemes tend to have same laser energy. This is because when the supply voltage is too high the time delay in the double-discharge scheme becomes too short thus sweeps out the preionization effect.

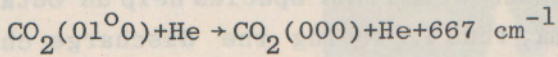
2. Effect of He

The result was shown in Fig. 5.

The role of helium in CO₂ lasers can be cast into several aspects: Firstly, the presence of He decreases the lifetime of lower laser level (10⁰) by more than a factor of five, but it does not affect

the population of the upper laser level (00^0_1).

Second, it helps the depopulation of CO_2 (01^0_0) level by the reaction:



which is the bottleneck step of the whole lasing process.

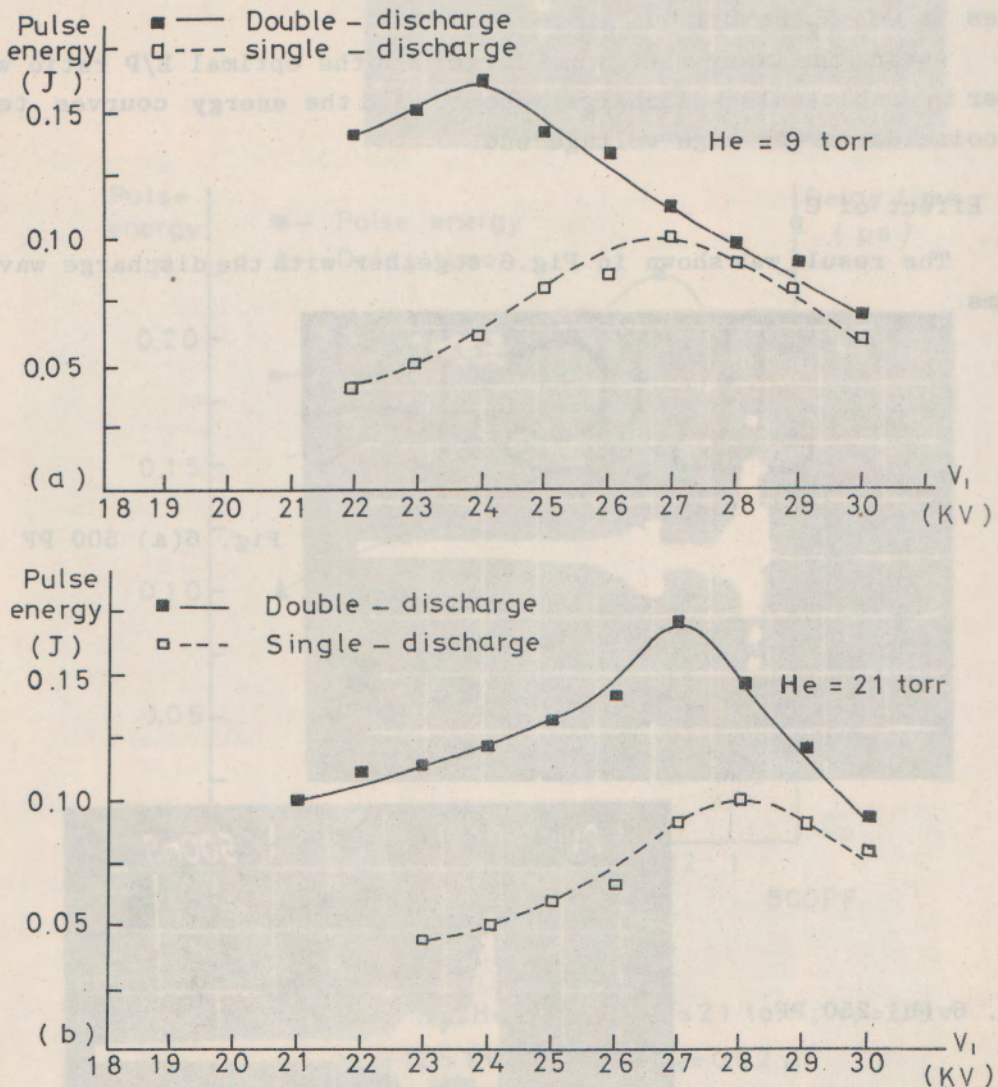


Fig. 5 Effect of He additive
 $\text{CO}_2 + \text{N}_2 = 6 + 3$ torr, $C_S = 0.02 \mu\text{F}$
 $C_P = 125 \text{ pF}$ $V_2 = 12.5 \text{ KV}$

Hence helium enhances CO₂ laser power very effectively.

Third, its high thermal conductivity keeps low gas temperature hence preventing the population of CO₂ (01⁰) level.

Furthermore, its collisions with other species help us obtaining a well diffused uniform plasma, thus improving the discharge characteristics. These explain why He is the main constituent gas in high pressure CO₂ lasers.

From Fig. 5 and Fig. 4(b) we see that the optimal ratio for these gases is CO₂:N₂:He=2:1:4.

Again, the laser energy was larger and the optimal E/P ratio was lower in double-pulse-discharge scheme. And the energy curves tend to coincide in the high voltage end.

3. Effect of C_p

The result was shown in Fig. 6 together with the discharge waveforms.

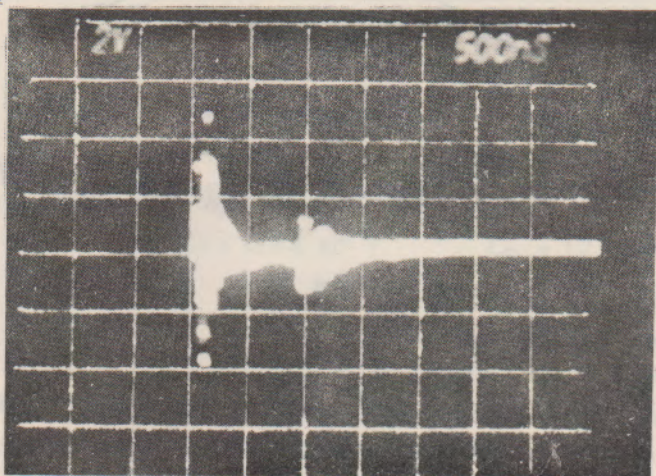


Fig. 6(a) 500 PF

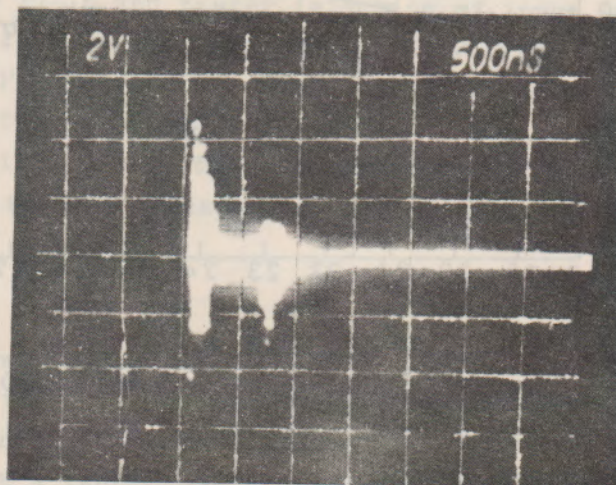


Fig. 6 (b) 250 PF

Fig. 6 (c) 1/8 x 500 PF

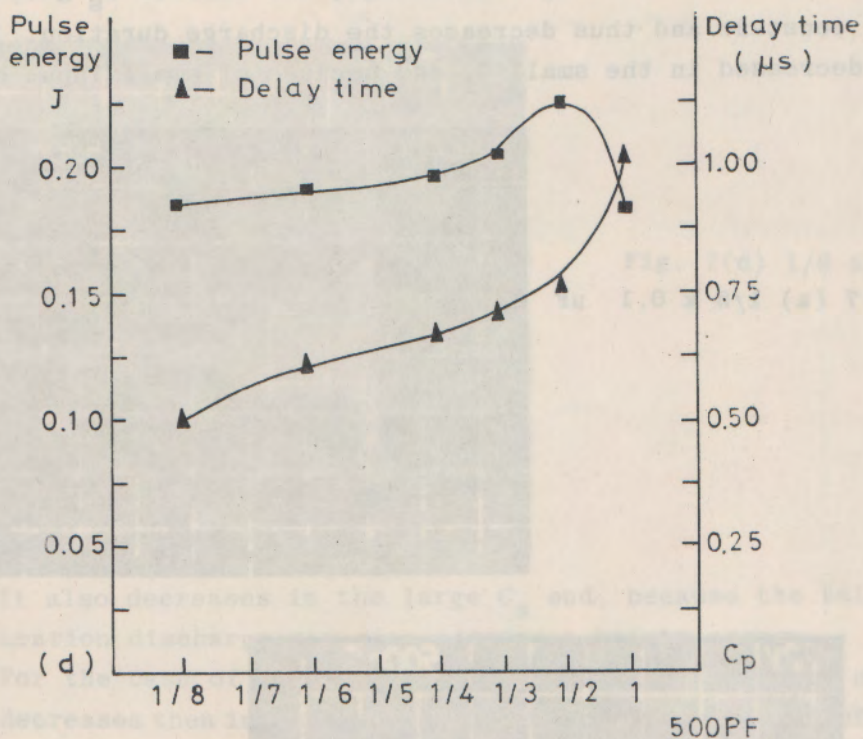
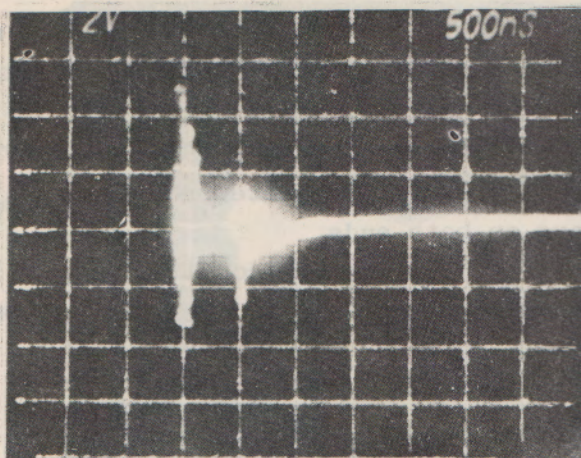


Fig. 6 Effect of C_p .

$CO_2 : N_2 : He = 2 : 1 : 4$; $p = 21$ torr ; $v_1 = 23Kv$
 $v_2 = 12.5$ kv $C_s = 0.02 \mu F$

As C_p increases from 1/8x500pF (eight 500pF capacitors in series) to 500 pF, the delay time between main discharge and preionization discharge increases from 500 nsec to 1 μ sec. This has an important effect on laser energy.

If the delay time is too short, the main discharge will occur before the plasma reaches uniform condition. It turns out that preionization is less efficient.

If it is too long, recombinations between electrons, ions and walls also tend to depreciate preionization effect. Thus laser energy decays on both ends.

Under the discharge condition of our laser tube the optimal time interval between these two discharges is 750 nsec, at $C_p = 250$ pF.

4. Effect of C_s

The result was shown in Fig. 7.

In the case of single-discharge, the smaller C_s gives shorter time constant and thus decreases the discharge duration. Laser energy decreased in the small C_s end because of small input energy.

Fig. 7 (a) $1/5 \times 0.1 \mu\text{F}$

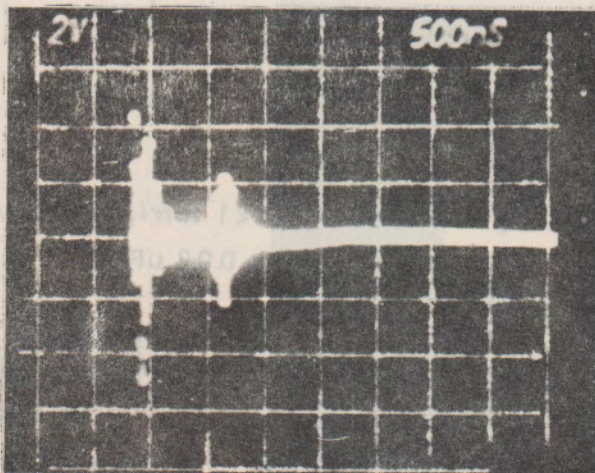
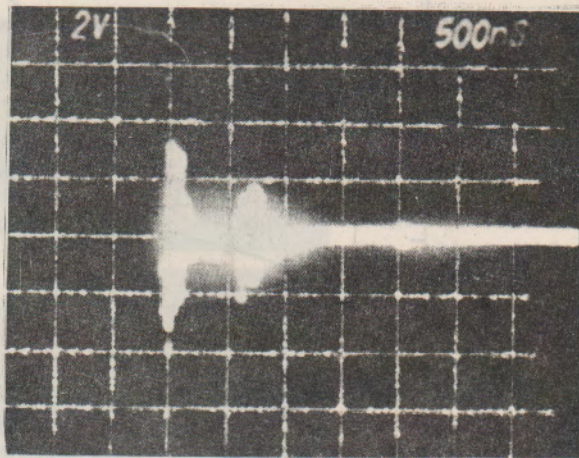


Fig. 7 (b) $1/6 \times 0.1 \mu\text{F}$

Fig. 7 (c) $1/8 \times 0.1 \mu\text{F}$

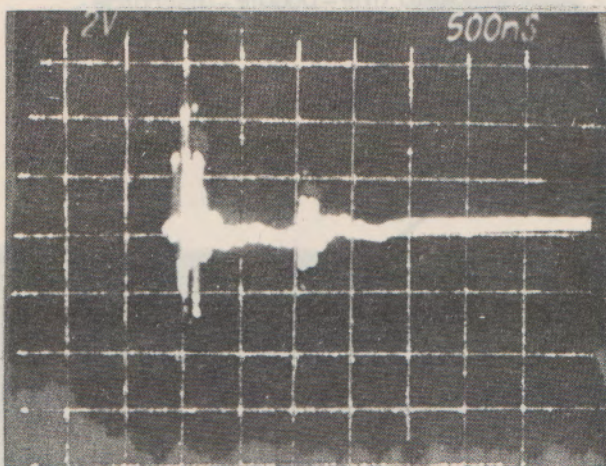
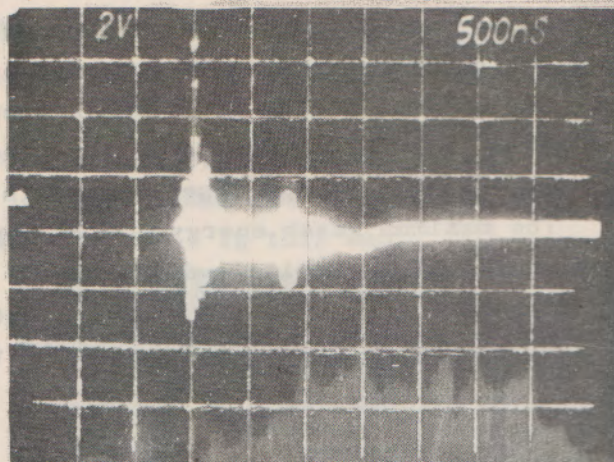


Fig. 7(d) $1/9 \times 0.1 \mu\text{F}$

It also decreases in the large C_s end, because the tail of a long duration discharge may give rise to a bright arc.

For the case of double-discharge, the main discharge duration first decreases then increases as C_s decreases from $1/5 \times 0.1 \mu\text{F}$ (five $0.1 \mu\text{F}$ capacitor in series) to $1/9 \times 0.1 \mu\text{F}$.

Since C_p was held at 250pF , the decreasing of C_s results longer charging time for C_p , that is, the delay time is longer. This can be seen in the photograph of Fig. 7.

For $C_s = 1/9 \times 0.1 \mu\text{F}$, the delay time is longer than $1 \mu\text{s}$, the preionization effect was somewhat lost and it gives longer main discharge duration (approaching to that of single-discharge scheme).

In the large C_s end, the time constant is large, and the plasma has not yet reach its optimal conditions (but is still better than

the small C_s end), the discharge impedance is still high. Thus the discharge duration is also longer, and laser energy is smaller.

The optimal degree of preionization occurs when C_s=1/6x0.1μF. This gives a smallest discharge impedance, therefore the discharge duration is shortest and laser energy is largest.

The maximum laser energy is 0.28 J by means of the scheme while it is only 0.17 J of single-discharge.

From Fig.7(e) we see that in the optimal case the time delay is also 750 nsec, which is consistent with the results of previous section.

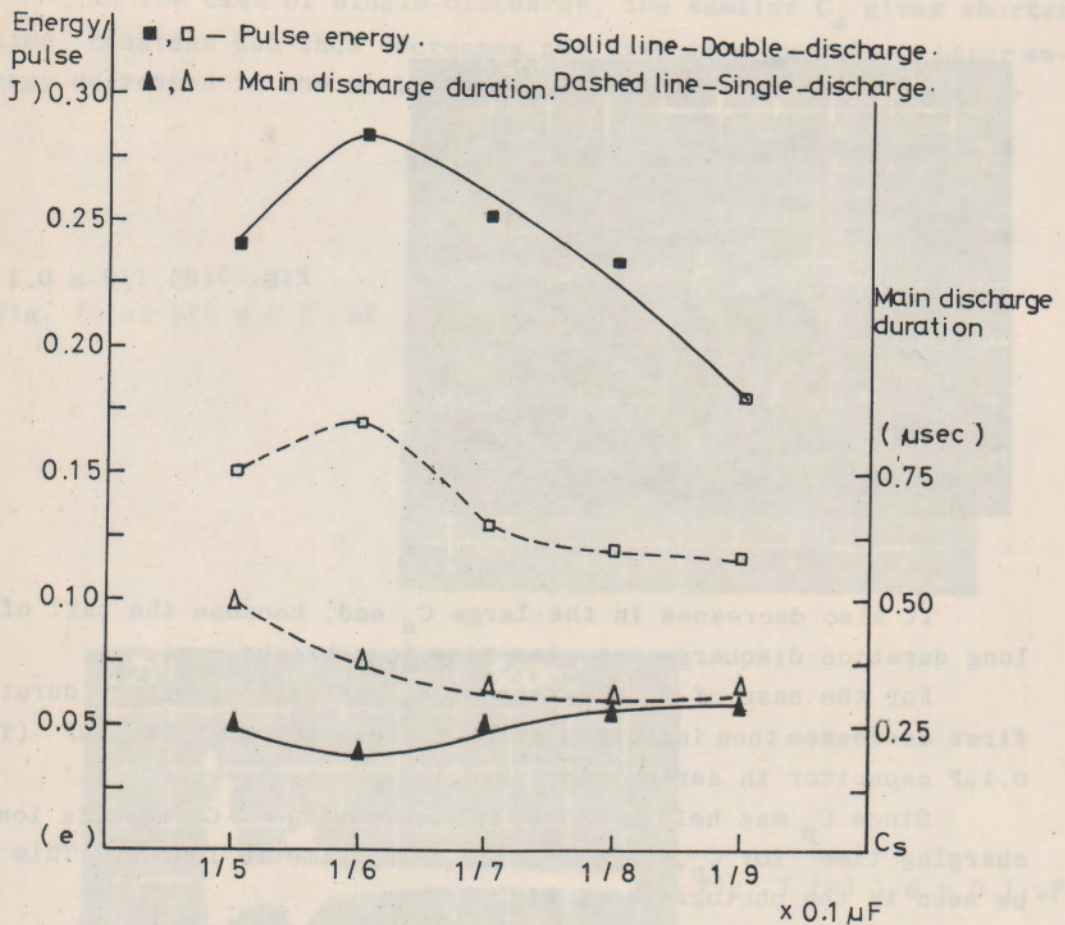


Fig.7 Effect of C_s.

CO₂:N₂:He = 2:1:4, p = 25 torr

v₁ = 23 kv, v₂ = 12.5 kv C_p = 250pF.

5. Effect of total gas pressure

The gas ratio was held as $\text{CO}_2:\text{N}_2:\text{He}=2:1:4$ and the result was shown in Fig. 8.

The main discharge voltage was kept at 23 KV. this is too high for low pressure end, that is, the plasma was "over heating" by pumping energy, thus laser energy is small in this end.

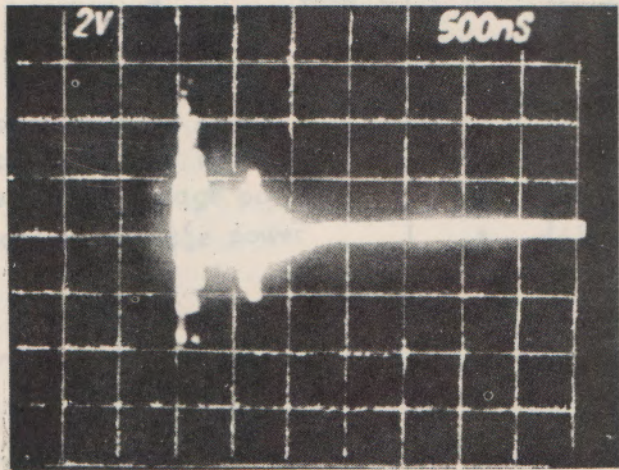


Fig.8(a) 21 torr

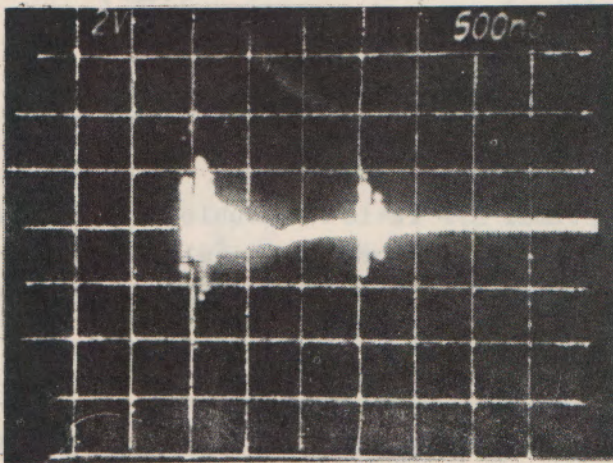


Fig. 8(b) 63 torr

In the high pressure end, the lifetime of the molecules was decreased. The pumping speed can not compensate the relaxation one. Furthermore, collisions and recombinations of plasma particles are much more rapidly in this case. The delay time is thus longer (Fig. 8(a), (b)) and the condition makes degrading the preionization effect resulting in some bright arcs. Therefore laser energy decays.

In order to have a better laser, we need improving the discharge scheme to get a faster pumping speed.

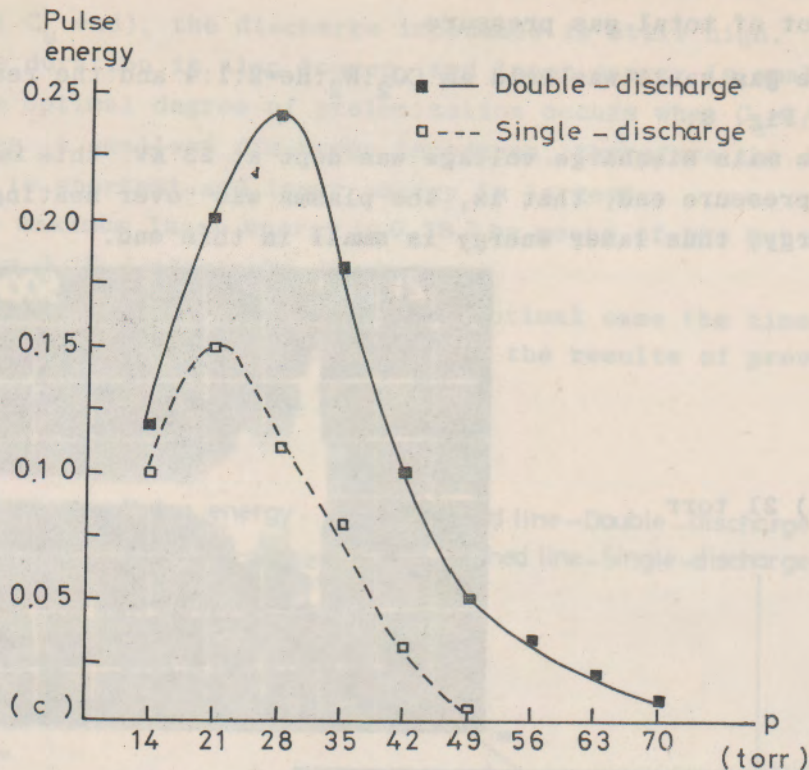


Fig. 8 Effect of total pressure.

CO₂:N₂:He = 2:1:4, v₁ = 23 KV,

v₂ = 12.5 KV, C_S = 1/6 × 0.1 μF, C_P = 250 pF.

Again, we see that the optimal E/P ratio for double-discharge is 13 V/cm-torr, which is lower than 15 V/cm-torr for single-discharge. And the laser output energy is increased from 0.17 J to 0.24 J.

6. Effect of repetition rates

The result was shown in Fig. 9.

Laser power of both discharge schemes rises rapidly as the pulse repetition rate increases. This is because the small amount of residue electrons and ions between two pulses make plasma somewhat uniform and facilitate laser discharge.

Laser energy decreases at high repetition rates. This is because the fast repetition operation gives exceeding heat to the gases, and large amount of gas dissociation products change the discharge characteristics of the gas. These two effects not only tend to generate some arcs but also degrade laser energy.

This degradation can be swept out by using a fast gas flow.

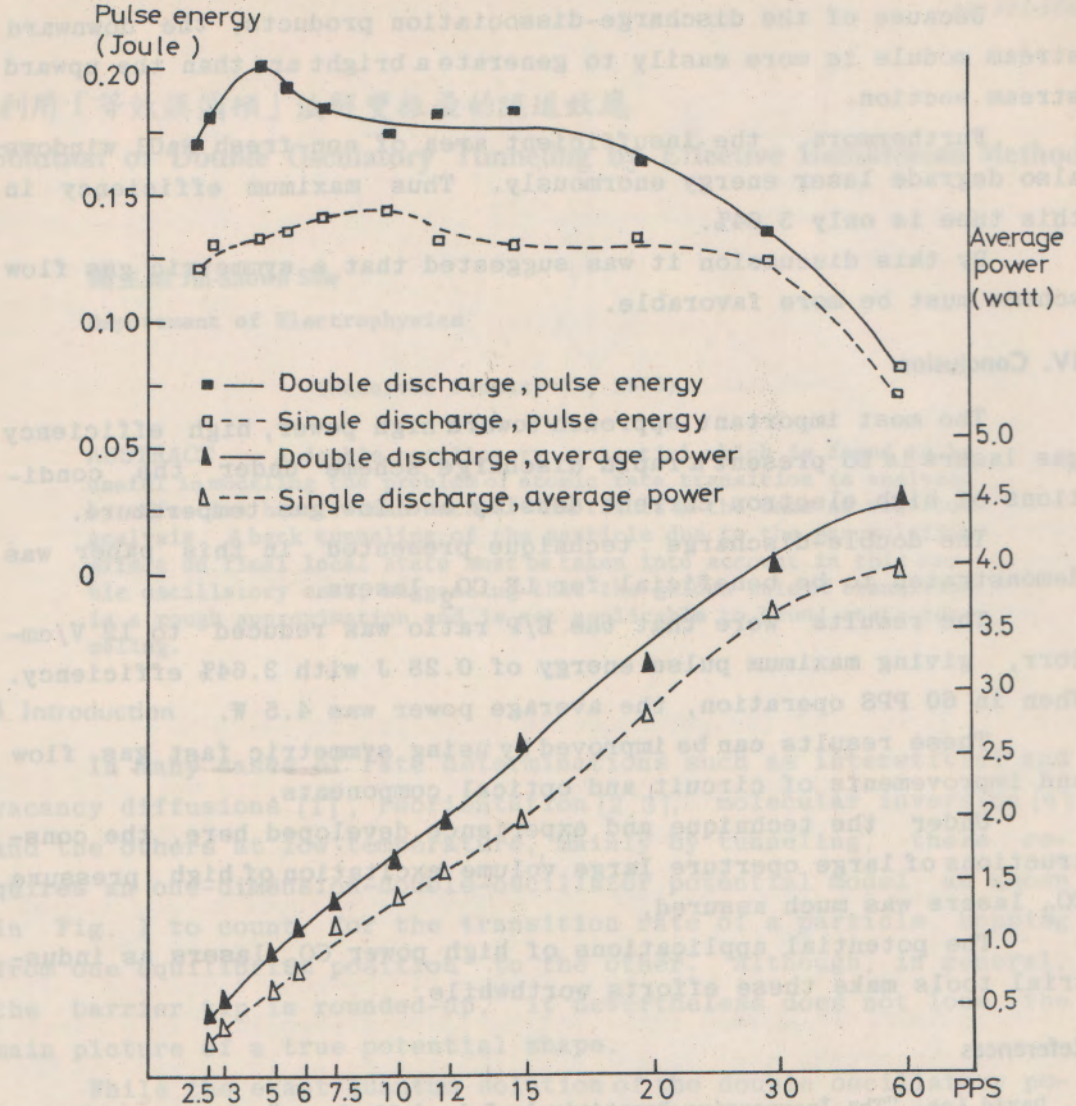


Fig. 9 Effect of pulse repetition rate.

$CO_2:N_2:He = 2:1:4$, $p = 26$ torr, $v_1 = 23$ KV.

$v_2 = 12.5$ KV, $C_s = 1/6 \times 0.1 \mu F$, $C_p = 250$ pF.

Once again we see that the maximum average power for double-discharge laser is 4.5 W which is larger than 3.9 W of single-discharge scheme, and both schemes are profitable for high repetition operations.

7. Effect of two-module construction

The two-module construction permits the excitation of twice volume with a given power supply at a given voltage. But there exists a slightly unsymmetric discharge between the two sections.

Because of the discharge-dissociation products, the downward stream module is more easily to generate a bright arc than the upward stream section.

Furthermore, the insufficient area of non-fresh NaCl windows also degrade laser energy enormously. Thus maximum efficiency in this tube is only 3.64%.

By this discussion it was suggested that a symmetric gas flow scheme must be more favorable.

IV. Conclusion

The most important approach toward high power, high efficiency gas lasers is to present a rapid discharge scheme under the conditions of high electron current density and low gas temperature.

The double-discharge technique presented in this paper was demonstrated to be beneficial for LE CO₂ lasers.

The results were that the E/P ratio was reduced to 12 V/cm-torr, giving maximum pulse energy of 0.28 J with 3.64% efficiency. When in 60 PPS operation, the average power was 4.5 W.

These results can be improved by using symmetric fast gas flow and improvements of circuit and optical components.

Under the technique and experience developed here, the constructions of large aperture large volume excitation of high pressure CO₂ lasers was much assured.

The potential applications of high power CO₂ lasers as industrial tools make these efforts worthwhile.

References

1. David Lee, "The Inexpensive Repetitively Pulsed CO₂ Laser", Institute of Electronics, National Chiao Tung University, Master Thesis, 1974.
2. P. K. Cheo, "Relaxation of CO₂ Laser Levels by Collisions with Foreign Gases", IEEE J. Quantum Electron., Vol. QE-4, No. 10, pp. 587-593, Oct. 1968.
3. P. K. Cheo, "Effects of CO₂, He, and N₂ on the Lifetimes of the 00⁰₁ and 10⁰₀ Laser Levels and on Pulsed Gain at 10.6", J. Appl. Phys., Vol. 38, No. 9, pp. 3563-3568, Aug. 1967.
4. Albert K. Laflamme, "Double Discharge Excitation for Atmospheric Pressure CO₂ Lasers", Rev. Sci. Inst., Vol. 41, No. 11, pp. 1578-1581, Nov. 1970.
5. Martin C. Richardson, ed. "A 300-J Multigigawatt CO₂ Laser", IEEE J. Quantum Electron., Vol. QE-9, No. 2, pp. 236-243, Feb. 1973.
6. W. L. Nighan, ed., "Investigation of the Plasma Properties of High Energy Gas Discharge Lasers", United Aircraft Research Lab. Report K-920833-5 (1971).