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A CO_2 GAS DYNAMIC LASER WITH FLOW RATE OF 10 Kg/sec

by

Chen Haitao

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A CO_2 GAS DYNAMIC LASER WITH FLOW RATE OF 10 Kg/sec

Chen Haitao
(Chinese Academy of Science, Institute of Mechanics, Gas Dynamic Laser Group)

I. PREFACE

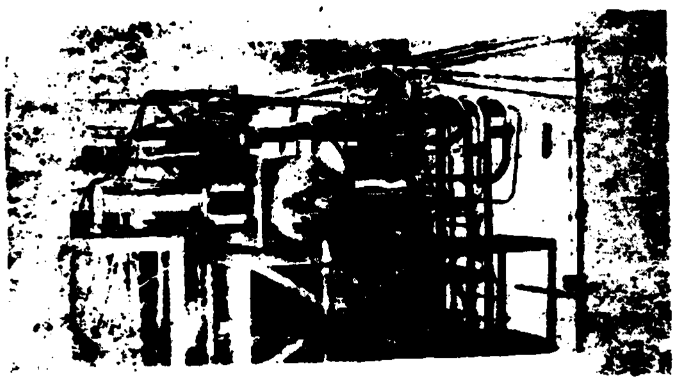
A gas dynamic laser is one of the highest power output laser systems at the present time. According to the reports abroad, in 1970 the continuous output of the combustion type could reach sixty thousands watts. In 1973, the shock tube type could reach an output level of forty thousand watts.

We began out research work on the development of gas dynamic lasers in 1971. Since then we have constructed three combustion type CO_2 gas dynamic systems of different sizes in order to carry out an investigation on the microscopic mechanical principle, non-equilibrium flow, the destructive effect of the high energy laser beam on the target, mechanical properties of the components, testing techniques, and the flexibility of promoting its applications both from experimental and theoretical aspects. This paper reports some of the experimental results of a 10 Kg/sec flow rate CO_2 gas dynamic laser.

II. EXPERIMENTAL APPARATUS AND WORKING PRINCIPLES

A 10 Kg/sec flow rate CO_2 gas dynamic laser is primarily composed of four major components, including a combustion chamber, a nozzle array, an optical resonance chamber, and a compressor (see photograph 1). CO, H_2 and air are burned in the combustion chamber to produce a

CO_2- H_2O - N_2 mixture at high temperature. When this gas mixture passes through the supersonic nozzle array and undergoes fast expansion, the number of lower energy CO_2 particles decreases with a reduction in the average dynamic temperature of the gas flow. Because of the longer relaxation time of the high energy level CO_2 particles, its number downstream from the nozzle remains the same (freezing of resonance energy). In addition, due to the continuous energy transfer from the first vibrational level of N_2 to CO_2, the number of higher energy level CO_2 particles keeps on increasing to reach a population inversion state. At this time, due to excitation radiation effects, a laser beam is emitted at the window of the resonance chamber. The wavelength is 10.6 micron. The residual heat is carried away by the gas flow and is discharged into the atmosphere through the compressor.



Photograph 1. 10 Kg/sec flow rate CO_2 gas laser.

The combustion chamber is made of a face plate, a combustion section, and a mixing section. On the face plate there are a total of 196 nozzles for CO, H_2 and air. In addition, there are four spark plugs. The diameter of the combustion section is 330mm. Cooled N_2 is first passed through a cooling jacket on the outer wall and then enters the mixing section to protect the combustion chamber.

The nozzle array is composed of 84 blades; its total width is 1020mm. The blade length is 80mm. The throat height is 0.6mm. The nozzle model line was obtained using the Atkin method. The nozzle area ratio is 20. The compression ratio of the compressor throat is 88%.

The width of the optical resonance chamber is 1020mm. Its height is 80mm and length 250mm. The side wall can mount two metallic mirrors 80mm in diameter in the front and back sequence, or four pieces of 40mm diameter metallic mirror up and down. Using mirrors of various radii of curvature a single path chamber, or a multiple path stable chamber, or a common focus unstable chamber can be formed. The output of the stable chamber uses a multiple-hole coupling. The output of the unstable chamber uses a ring coupling. The reflection coefficient of the mirror is 96-98%.

The N_2 and H_2 used were supplied by the gas factory of the Chinese Academy of Sciences. The air was taken from the atmosphere. CO was prepared by burning charcoal and then washing with NaOH.

The entire operation was controlled automatically by the control desk. Upon the start, all the valves were opened and ignition took place. It automatically ceased after 5 seconds.

III. MEASURING TECHNIQUE

The gas flow rate was measured using a critical nozzle. The temperature of the gas was measured using a platinum-rhodium platinum thermocouple. The composition of the combustion gas was determined using a spectrograph. The Mach number of the gas flow in the optical chamber region was obtained by measuring the pressure /51
of a transducer according to

$$\frac{p_0}{p}=\left(1+\frac{k-1}{2}M^2\right)^{\frac{k}{k-1}} \quad \text{(A)}$$

where p is the pressure of the observation point, P_0 is the pressure of the combustion chamber, k=1.37 which is the specific heat of the gas.

Using a 6 watt CO_2 laser beam as the probing beam to penetrate the optical chamber, the light intensities, before and after the experiment, were measured in order to determine the small signal gain of the excited medium per centimeter according to the following equation:

$$g = -\frac{1}{L} \ln \frac{I}{I_0} \qquad \text{(B)}$$

For a single path chamber, L=102cm; for a triple reflection multiple path chamber, L=306cm. A NaCl scatterer was placed in front of the detector to stabilize the signal.

Two methods were used to measure power. One is a hole burning method. A concave mirror was used to concentrate the output beam to melt an organic glass rod. On the basis of the difference in the weight of the glass rod before and after the melting and the melting time, the power output was obtained:

$$P = 3100 \frac{\Delta g}{\Delta t} \qquad \text{(C)}$$

In order to drive the vapor of the organic glass, N_2 was blown onto the target in the experiment. The other method is to use a power measuring device. The photon energy entering the power measuring device causes a change in the output signal (in millivolts). Then

$$P = 1200 \frac{\Delta(mV)}{\Delta t} \qquad \text{(D)}$$

The beam diffuse angle was measured using the following two methods. The first one is a hole burning method. The angle was obtained by directly measuring the diameter of the burnt hole (mm) of an organic glass plate:

$$\theta = \frac{d}{F} \qquad \text{(F)}$$

where F=970mm which is the focus of the concave mirror. The other method is a two-dimensional scanning method. The focused output beam was guided into a rotating cyclinder with tiny holes and thermisters were used to measure the light intensity penetrating through the tiny hole (Figure 1). Each penetrating light beam is equivalent to the scanning of the focal spot once, 1mm apart. The longest scanning time corresponds to the diameter of the focal spot. It is also possible to consider the number of scans as the diameter of the focal spot in millimeters. Based on this, the diffuse angle can be obtained using the above equation.

Two methods were used to adjust the optical chamber before the experiment. An illuminated cross was placed at the output window. From the center hole of the total reflective concave mirror, we observed the overlapping of all the images. By adjusting the angles of all the reflecting mirrors, the images of the cross were made to superimpose. Another way is an interference chamber adjustment method, using a He-Ne laser beam to directly shine into the optical chamber through the hole on the concave mirror. By adjusting all the reflecting mirrors, a concentric ring interference pattern was obtained at the output window.

Using a 1mm diameter copper wire placed at one side of the light exit hole, a thermister was used to detect the reflected light and the light exit time was shown on the oscilloscope.

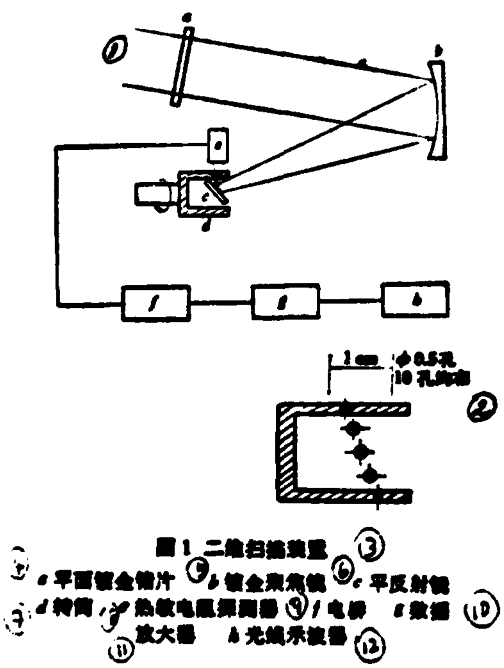


Figure 1. Two dimensional scanning set up.

Key: 1--laser beam; 2--Ø 0.5 hole, 10 holes evenly distributed; 3--two-dimensional scanning set up; 4--a)gold-plated flat germanium plat; 5--b)gold-plated concentrating mirror; 6--flat reflective mirror; 7--rotating cylinder; 8--thermister detector; 9--electrical bridge; 10--data; 11--amplifier; 12--light oscilloscope.

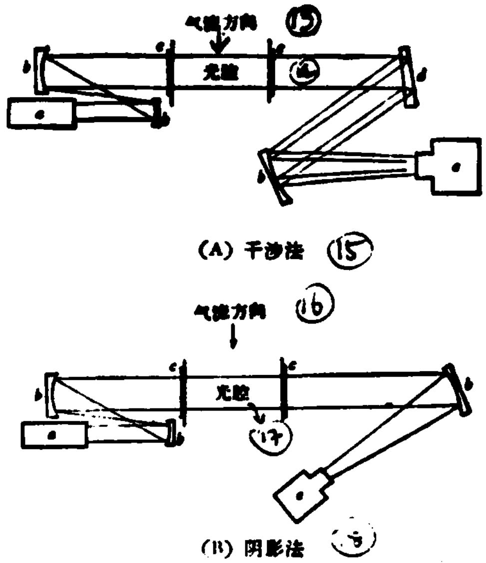


图2 流场测量光路

a He-Ne 激光器 b 凹反射镜 c 腔窗口，安放有平面晶体 d 平晶 e 高速摄影机

Figure 2. Optical path used in measuring flow field.

Key: 13--direction of gas flow; 14--optical chamber; 15--(A) interface method; 16--direction of gas flow; 17--optical chamber; 18--(B) shadow method; 20--He-Ne laser; 21--concave reflective mirror; 22--window of optical chamber; 23--with flat crystal in place; 25--high speed movie camera; 24--flat crystal

The flow field measurement included two methods, i.e., /52
the shadow method and the interference method (Figure 2). A He-Ne laser beam after focusing in the optical chamber was used to obtain the optical chamber from field pictures by a high speed movie camera which is the shadow method. In the interference method, after passing through the optical chamber, the He-Ne laser beam was reflected by a flat crystal. A high speed camera was used to obtain the interference pattern.

The spectral line of the laser beam was determined using a CO_2 spectrometer.

IV. OUTPUT LIGHT EXPERIMENT

On the basis of the experimental results obtained using a 1 Kg/sec flow rate apparatus, the optimal working parameters are: combustion chamber pressure 23 Kg/cm^2, combustion chamber temperature 1300°K, Mach number of the gas flow M=4.5, and combustion gas composition CO_2 13%, H_2O 1%, N_2 86% (molecular ratio). The 10 Kg/sec flow rate set up was tested using these parameters. But the form of the optical resonance chamber was changed in order to obtain the maximum output power and minimum light beam diffuse angle.

The combustion chamber adopted a structure such that a pre-ignited H_2-O_2 flame was used to ignite CO. The firing procedure went along smoothly. The three temperature sensing points at the exit of the mixing section measured 1188°C, 1200°C, and 1104°C, respectively. It was considered that the mixing of the combustible gas was satisfactory. The operation was steady in the experiment. In the first 1.5 seconds, the temperature and pressure of the combustion chamber rapidly reached stable values. The next 3.5 seconds of time was the stable light emitting time. The combustion chamber and the nozzle array were found to be able to sustain high temperature and high pressure. After over eighty tests, no serious damage existed. Because the nozzle array was assembled using a tinker toy type of arrangement, the blades can freely expand and contract; no bending or distortion has been observed.

The small signal gain of a single path in the optical chamber was measured to be 0.5%/cm. For a triple superimposed path, the gain was 0.26%/cm. The experimental error was 0.08%/cm.

Light emitting experiments were carried out using a single path stable chamber, a triple reflective path stable chamber, a single path unstable chamber, and a triple path unstable chamber. The major results are shown in Table 1. The curvatures of the mirrors used in the experiments, the coupled output efficiency (%) and the output power were also listed in the table. The diameter of the mirror was 80mm.

More experiments were performed using the first hole in the front to emit the laser beam in the single path mode. The maximum power output reached 33000 watt. The burning pattern on an organic glass plate by multiple hole coupled output is shown in Photograph 2. After focusing, the laser beam could penetrate a 10mm thick steel plate in 3.5 seconds under the condition that O_2 was delivered to the surface. The diameter of the hole was 17.5mm. Simultaneously, the steel plate behind it was melted and formed a 6.2mm deep hole (see Photograph 3). Photograph 4 shows the situation during the melting process.

Table 1. Typical Light Emitting Experiment

表1 典型出光实验

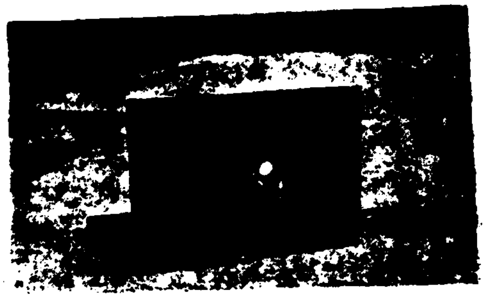
② 光腔型式	曲率半径(米) ③				④ 耦合率 %	⑤ 输出功率 (瓦)
	R_1	R_2	R_3	R_4		
⑥ 单程稳定腔 (多孔出光)	7.02	∞			11.19	1670[illegible]
	14.4	7			18	3300[illegible]
	7.02	∞	6.76	∞	10	31[illegible]
⑦ 折叠稳定腔	8.5	∞	∞	∞	13	1060[illegible]
⑧ 单程非稳腔	10	−8.25			35	1120[illegible]
⑨ 折叠非稳腔	14	∞	∞	−8.25	63	1000[illegible]

Key: 2--type of optical chamber; 3--radius of curvature; 4--coupling efficiency %; 5--power output (watt); 6--single path stable chamber (multiple hole); 7--multiple path stable chamber; 8--single path unstable chamber; 9--multiple path unstable chamber.

*Mirrors No. 1 and No. 2 represent the two holes on the right and left of the first row. Mirrors No. 3 and No. 4 represent the two holes on the second row in the chamber.

**Concave mirror has positive radius of curvature; convex mirror has negative radius of curvature; the radius of curvature for a plane mirror is infinity.

Photograph 2. Organic glass plate melted by multiple hole coupled output.



Photograph 3. The penetration of 100mm thick steel plate by 33000 watt laser beam.

The experiment using the second hole alone only resulted in 6500 watt. When both holes were used, the output of the second hole was weak. The triple reflection experiment only gave 10600 watts.

In order to obtain a single mode output and to improve the quality of the laser beam, we carried out experiments with a common focus unstable chamber. The single path power output was 11200 watts /53 which was only 1/3 of that of a stable chamber. It was capable of melting the organic glass rod to form a 18mm diameter, 160mm deep, long and conically - shaped hole (see Photograph 5). The power output of a triple reflection unstable chamber still remained at approximately 10000 watts.

Photograph 4. The melting of the steel plate.

Photograph 5. The melting of organic glass rod by a 11000 watt output from unstable chamber. The hole is long, slender, and conically shaped.

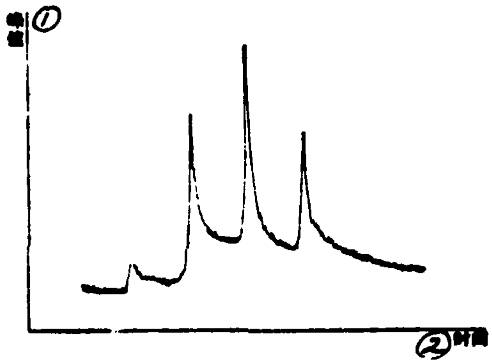


Figure 3. The measurement of diffuse angle using two-dimensional scan.

Key: 1--peak value; 2--time.

V. THE MEASUREMENT OF DIFFUSE ANGLE

The hole burning method was used to determine the laser beam diffuse angle for single or multiple path unstable chambers formed by 80 and 40mm diameter metallic mirrors. However, no reliable data were obtained. This is because during the melting of the organic glass the holes appeared to be conically tipped and cylindrically shaped near the bottom. Thus, the diffuse angles tended to be too large, approximately 13 seconds of a radian.

A two-dimensional scan was carried out to measure the diffuse angle of the up-and-down type of reflective unstable chamber formed by 40mm diameter metallic mirrors. Four peaks were shown on the oscilloscope. The measured diffuse angle was 4 seconds of a radian. During the measurement, two different filter plates were used: one was a copper plate with holes and the other was a gold plated germanium plate.

The diffraction limit of the CO_2 laser beam from a 40mm diameter hole was 0.32 seconds of a radian. Therefore, the 10 Kg/sec flow rate CO_2 gas dynamic laser beam has a diffraction limit which is six times that of the diffuse angle with the same hole diameter.

Through the measurement of the flow field, we found that there were two apparent slanted shock waves on the upper and lower side of the throat of the nozzle blade. They intersected at a 40° angle in the excitation region of the optical chamber. A He-Ne laser was used to pass through the optical chamber. Using a concave mirror to focus the beam, it was possible to determine the variation of the focal spot diameter back and forth. It was found that when shock wave existed, the diameter of the focal spot was three times that when shock wave was not in existence.

In order to determine the effect of the shock wave line on the beam diffuse angle, we carried out separate experiments through the shock wave and away from the shock wave. In the former case, the shock wave passed through the optical path created by 40mm diameter mirrors. In the latter case, the optical path formed by 40mm diameter mirrors was located in the space between the two shock wave fronts. Experimental results indicated that the diffuse angle was 6 seconds of a radian going through the shock wave and only 3 seconds of a radian when the shock waves were avoided. Therefore, it is clearly demonstrated that the diffuse angle of the laser beam can be reduced to 3 seconds of a radian by eliminating or weakening the shock wave in the optical chamber.

The laser beam output from the unstable chamber was determined to be the P(20) branch using an optical spectrograph. Its corresponding wavelength was 10.59 micron.

VI. CONCLUSIONS

Using a supersonic expansion technique in a 10 Kg/sec flow rate CO_2 gas dynamic laser unit to create a population inversion of the CO_2 particles, we obtained a 33000 watt multiple mode continuous output. The power ratio reached 3000 watt sec/ Kg. Single mode output was the P(20) branch with a power of 11200 watts and a beam diffuse angle of 4 seconds of a radian. After eliminating the effect of shock wave, the diffuse angle can be reduced to 3 seconds of a radian.

The level of standard abroad for this type of system was 4000 watt sec/Kg in power ratio. The diffuse angle was twice that of the diffraction limit. Our results were below standards compared to those in foreign countries.

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