Gasdynamic lasers

The population inversion necessary for lasing action in a gas can be induced by rapid expansion—without external pumping—of a hot gas mixture to supersonic speeds

Edward T. Gerry* *Avco Everett Research Laboratory*

It is not enough to depend upon diffusivity to dissipate the heat from a gas laser. Under the circumstances, average power outputs are too limited. By generating flow within the gas and deriving the benefits of forced convection, performance is improved. But if flow can be used to improve power outputs, it also can be used to advance a step further and generate the conditions that are necessary for lasing action—thereby creating a gasdynamic laser. This article covers the theory behind such a device and describes an experimental unit that has proved the merit of the concept.

The most fundamental limitation on the average power output of a laser is the waste energy resulting from inefficient operation. This waste energy may appear in the form of excited metastable states or simply as heat.

Figure 1 presents an analysis of the methods by which waste energy is removed. Most laser devices, whether solid or gas, have an active medium in the form of a long, thin cylinder. In the case of a solid, waste energy simply is conducted to the wall where it is removed by a coolant; in the case of a gas laser, energy is disposed of by diffusion of metastable states or heat to the outer walls of a cylindrical container.

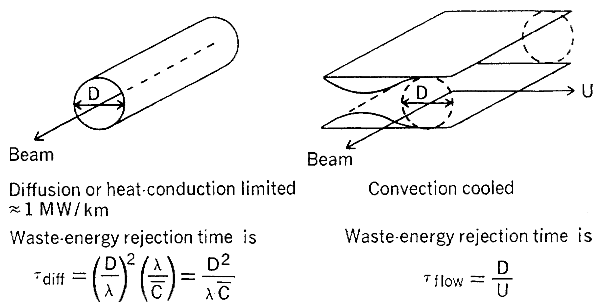


FIGURE 1. Comparison of characteristic times related to the removal of waste energy from cooled and uncooled high-average-power lasers.

With only diffusion or heat conduction to remove waste energy, a laser device, on an average-power basis, is limited to a maximum power of the order of 1 kW/m of solid-rod or gas-tube length—regardless of the diameter. However, by using high-speed flow to remove the waste energy more quickly, the average power capabilities of the device can be increased.†

For typical gas lasers, the factor by which the average power density can be increased through the use of high-speed flow[1] ranges from 10^3 to 10^5. In addition, since the flow time is independent of gas density, the density can be increased to provide still greater powers. Thus, high-speed flow can lead to larger devices that provide significantly greater average power densities than are achievable with diffusion-controlled lasers.

Table I indicates the application of flow to various classes of lasers. In electrically pumped lasers, flow can be used for removing waste energy. Excited by electron impact of, typically, "volts" energy, such electrically excited lasers as CO_2[2–7] operate at 10 μm (in the infrared); carbon monoxide[8, 9] operates around 4 μm; the copper-vapor laser[10, 11] operates in the green; and the nitrogen laser[12, 13] operates in the ultraviolet. All of these, and others, are potential candidates for the application of

* Article adapted from a paper presented by E. T. Gerry at the American Physical Society meeting, Washington, D.C., April 1970.

† In a diffusion-controlled laser, waste energy is rejected in a characteristic time approximately that of the diffusion time T_{diff}. Because the process is random walk, T_{diff} is equal to the square of the number of mean free paths $(D/\lambda)^2$ during which the energy diffuses multiplied by the mean free time between collisions $(\lambda/\bar{C})$ and, therefore, is $D^2/\lambda\bar{C}$. Here D is the characteristic dimension of the tube, λ is the mean free path, and $\bar{C}$ is the molecular speed. But if the gas is moved at a speed U in a flowing system, waste energy is rejected in a time equal to D of the tube divided by U—i.e., D/U.

Thus, for the same active volume and gas density, the ratio of the power achievable with a stagnant and with a flowing-gas laser is simply the ratio of the characteristic times, which, as shown in Fig. 1, is equal to the characteristic dimension divided by the mean free path times the flow velocity divided by the mean molecular speed—i.e., $DU/\lambda\bar{C}$. Since the speed of sound in a gas is approximately the same as the mean molecular speed, the velocity ratio essentially is the Mach number.

I. Application of flow to various types of gasdynamic lasers

Type of Laser	Use of Gas Flow	Wavelength	Gases Used
Electrically pumped	Removal of waste energy (heat, excited states)	Widest range possible for efficient operation	CO_2, N_2, CO, Cu vapor
Chemically pumped	Removal of waste energy, temperature control, mixing, replenishing reactant	2–6 μm; longer in hybrid systems	F + HCl, F + H_2; hybrid: F + H_2 → CO_2* (where * signifies excited molecule)
Thermally pumped	Production of gas inversion from equilibrated hot gas; removal of waste	8–14 μm for efficient operation	CO_2 at 10.6 μm

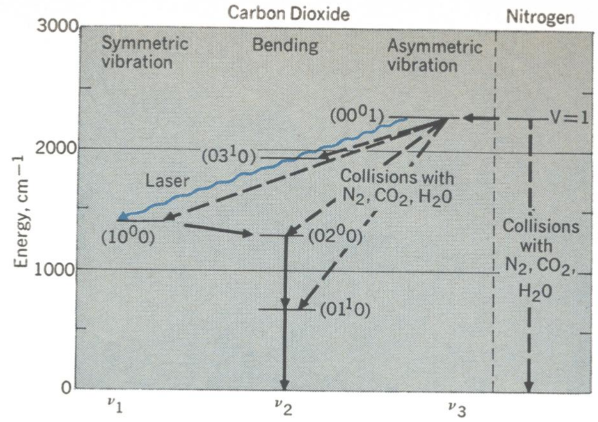


FIGURE 2. Exchanges between energy levels in a CO_2-N_2 laser. Sequential numbers relate respectively to asymmetric-stretch, bending, and symmetric-stretch mode levels. Superscript accompanying bending mode indicates the plane of vibration. V = 1 denotes first excited vibrational state.

high-speed flow cooling.

In addition to electrically excited gas lasers, there are gas lasers that are either chemically or thermally pumped. But whereas the electrically pumped gas laser benefits from the application of flow only to the extent that waste energy is carried away, the chemical and thermal types depend on the flow for their lasing action.

Flow is essential to a high-power chemical laser system to replenish reactants that are consumed in the production of population inversion. (In a chemically pumped system, the active laser species is a direct product of a chemical reaction, is produced by this reaction in an excited state, and subsequently is lased.) Also in a high-speed, flowing-gas chemical laser, active variation of flow parameters may be used to achieve temperature or reaction-rate control within the laser cavity.

For efficient operation, chemical lasers typically operate in the 2- to 6-μm region of the infrared. (The chemical energy released in a reaction generally has a value corresponding to a wavelength in this range.) Operation efficiently can be extended further into the infrared in a hybrid system—wherein the energy in the excited product molecule is transferred to another molecule, which then becomes the active laser species. Examples of such chemical laser systems include those making use of the F + HCl[14,15] exchange reaction to produce excited HF, and the F + H_2 reaction,[16,17] which also produces excited HF. This excited HF energy is transferred to CO_2 and produces laser action at 10.6 μm.[18]

Gasdynamics

The final type of laser that will be described—and to which the rest of this article will be devoted—is the thermally pumped gasdynamic laser. With it, flow is used to create an inversion from what is, initially, a completely equilibrated hot gas. A thermally pumped system starts with a hot equilibrium gas mixture in which there is no population-energy inversion. The inversion is produced "gasdynamically" by rapid expansion through a supersonic nozzle.[19]

Because a hot gas is the basic energy source, these lasers typically will operate efficiently in the 8- to 14-μm-wavelength band. The prime example of this type of laser is the nitrogen–CO_2 gasdynamic laser, operating at 10.6 μm in the standard CO_2 laser transition.

The production of vibrational nonequilibrium in CO_2 in a high-speed flow was demonstrated by Kantrowitz[20] in connection with the development of a gasdynamic method for measuring vibrational relaxation times. The inversion-production gasdynamic-method laser, in its most general form, was suggested by Basov and Oraevskii.[19] The possibility of population inversion in N_2-CO_2 mixtures by rapid expansion through a supersonic nozzle was suggested by Konyukhov and Prokhorov.[21] A similar gasdynamic approach—differential radiative relaxation in a fast expansion of an arc-heated plasma—was suggested by Hurle and Hertzberg.[22]

Figure 2 shows an energy-level diagram of the carbon dioxide and nitrogen molecules,[23] indicating the important vibrational relaxation processes that occur in such a mixture. The CO_2 gasdynamic laser typically involves a gas mixture that is mostly nitrogen, and approximately 10 percent carbon dioxide and one percent water. (Mixtures involving helium instead of water are also possible.)

Nitrogen, a simple diatomic molecule, has only one vibrational mode. Energy can be lost from this mode by collisions with nitrogen, CO_2, and water,[24] returning the excited molecule directly to the ground state. Carbon dioxide, being a linear triatomic molecule, has three basic modes of vibration: asymmetric stretch, which forms the upper laser level; symmetric stretch, which forms the lower laser level; and bending.

The energy-exchange process in the gasdynamic laser includes several transfers: (1) The very close near-resonance between nitrogen and the first asymmetric-stretch level of CO_2 causes efficient transfer of energy between these modes. Typically, the probability of this transfer at room temperature is one in every 500 collisions.[25,26] (Direct deactivation of nitrogen is relatively unimportant and energy is lost from the mixture generally through the CO_2 vibrational levels.) (2) Energy can be lost from the asymmetric-stretch mode of CO_2 by collisions with nitrogen, CO_2, and water—most probably transferring into the symmetric-stretch and bending modes of CO_2.[24,25,27-29] (However, lasing occurs only for transitions from the first asymmetric-stretch mode to the first symmetric stretch.) (3) The Fermi resonance between the bending and symmetric-stretch modes of CO_2 tightly couples these modes, Therefore, excitation energy is extracted from the lower laser level by deactivation of the bending mode—a process that can occur during collisions with all gas species, but principally water.[24]

Principle

The basic principle of the gasdynamic laser is to expand the gas rapidly through a supersonic nozzle to a high Mach number. The object is to lower the gas-mixture temperature and pressure downstream of the nozzle in a time that is short compared with the vibrational relaxation time of the upper-laser-level system (consisting of the asymmetric-stretch mode of CO_2 coupled with the nitrogen). At the same time, by addition of the catalyst (water or helium), the lower level relaxes in a time comparable to, or shorter than, the expansion time. Because of this rapid expansion, the upper-laser-level system cannot follow the rapid change in temperature and pressure and thus becomes "hung up" at a population characteristic of that in the stagnation region. Because the vibrational relaxation times associated with the upper level are long, the population will stay "hung up" for a considerable distance downstream of the nozzle. This process is known as vibrational freezing.

A basic CO_2 gasdynamic laser is presented in Fig. 3. At the top is a schematic of a supersonic nozzle. The gas flow runs from left (the stagnation region, which contains a hot, equilibrium gas mixture) to the right. A typical set of stagnation characteristics is indicated for a mixture of 7.5 percent CO_2, roughly 90 percent nitrogen, and one percent water: a temperature of 1400°K and a pressure of 17 atmospheres. (It is important to note that this is a completely equilibrated gas mixture. There is no inversion present, and since it is in an equilibrium state, this mixture can be produced in any desired way. For example, it may be produced by simply heating in a heat exchanger or nuclear reactor. Alternatively, it may be produced by combustion of a suitable fuel or by heating in a shock tube.) Typical downstream characteristics for the gasdynamic laser are an area ratio (with respect to the throat) of 14, a throat height of 0.8 mm, a Mach number of the order of 4, a pressure of about 0.1 atmosphere, and a temperature near ambient.

Figure 3(B) shows how the energy is distributed between the various degrees of freedom of the gas in a CO_2 gasdynamic laser. In the stagnation region, most of the energy is associated with the random translation and rotation of the gas molecules and 10 percent (or less) is associated with vibration. As the gas is expanded through the supersonic nozzle, the random translational and rotational energies are converted into the directed kinetic energy of flow. The vibrational energy, if it remained in equilibrium with the gas temperature, essentially would disappear downstream of the nozzle. Because of the rapid expansion, however, the vibrational energy remains "hung up" and its vibrational temperature is characteristic of that upstream of the nozzle.

Looking at this in terms of populations [Fig. 3(C)], it is apparent that the population of the lower level exceeds that of the upper level in the stagnation region, which is typical of an equilibrated gas mixture. As the gas is expanded through the nozzle, the upper-level population drops just a little bit and then remains essentially level. The lower-level population diminishes rapidly within the nozzle, continues to decrease, and virtually disappears a few centimeters downstream. Thus, downstream of the nozzle, the population of the upper level is characterized by a temperature like that of the stagnation region and the population of the lower level is characterized by a temperature like that of the downstream region. Inversion begins approximately one centimeter downstream of the nozzle throat and continues, for the gas conditions indicated in Fig. 3, for about a meter downstream of the nozzle. Because of the high gas densities involved and the high-speed flow downstream of the nozzle, an inversion capable of operation at very high powers is achieved.

General considerations

In Fig. 4, some additional considerations regarding the operation of the gasdynamic laser are presented. The flow tube has a stagnation pressure P_{stag}, stagnation tem-

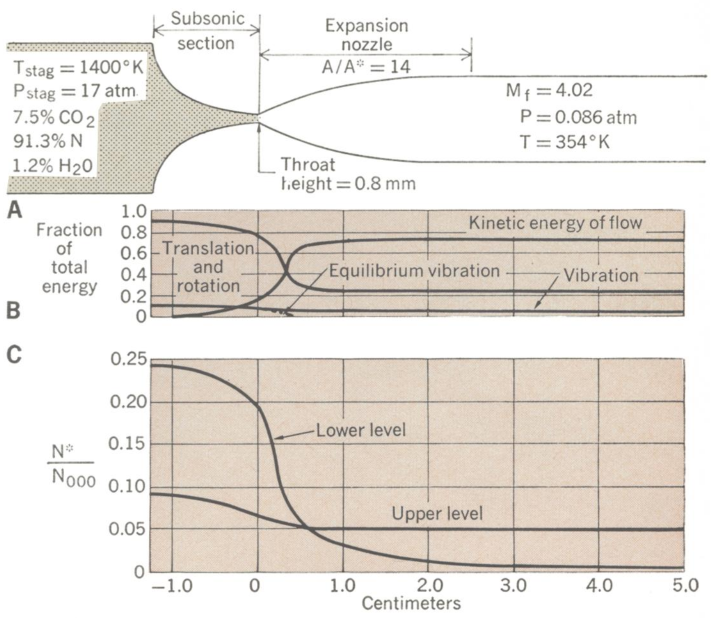
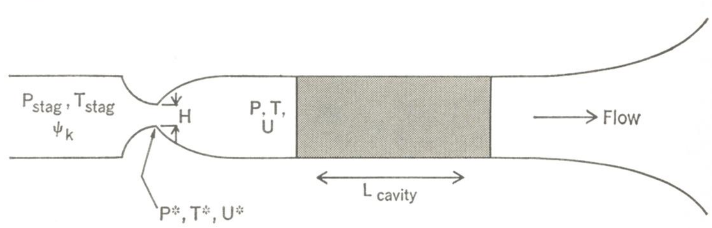


FIGURE 3. Existing conditions for a specific gas laser. N_{000} is the ground-state population. N* is an arbitrary excited state; two such states—the 100 lower and 001 upper level—are shown.

FIGURE 4. General conditions necessary for gasdynamic lasing. Diffuser (right) is only representational.



perature T_{stag}, and concentrations of species ψ_k in the stagnation region. The nozzle has a throat height H, with pressure, temperature, and velocity at the throat indicated by the starred quantities. Downstream, P, T, and U indicate pressure, temperature, and velocity in the laser cavity region—signified by the grey area—where energy is removed.

First, consider the energy that is available in the gas-dynamic laser. Per unit mass, it is essentially the vibrational energy stored in the nitrogen and CO_2 asymmetric stretch upstream of the nozzle throat. For a 10 percent CO_2, 90 percent nitrogen mixture at a stagnation temperature of 1400°K, the available laser energy (based on freezing the upper-level vibration at the stagnation temperature) is 35 J/gm of gas or 35 J/gm/s of gas flow. This maximum available energy will, of course, increase as the stagnation temperature is increased.* In any practical system, however, all of the energy available cannot be extracted because of inefficiencies and other constraints in the system. Typically only one third to one half of this available energy can be extracted from a well-designed system.

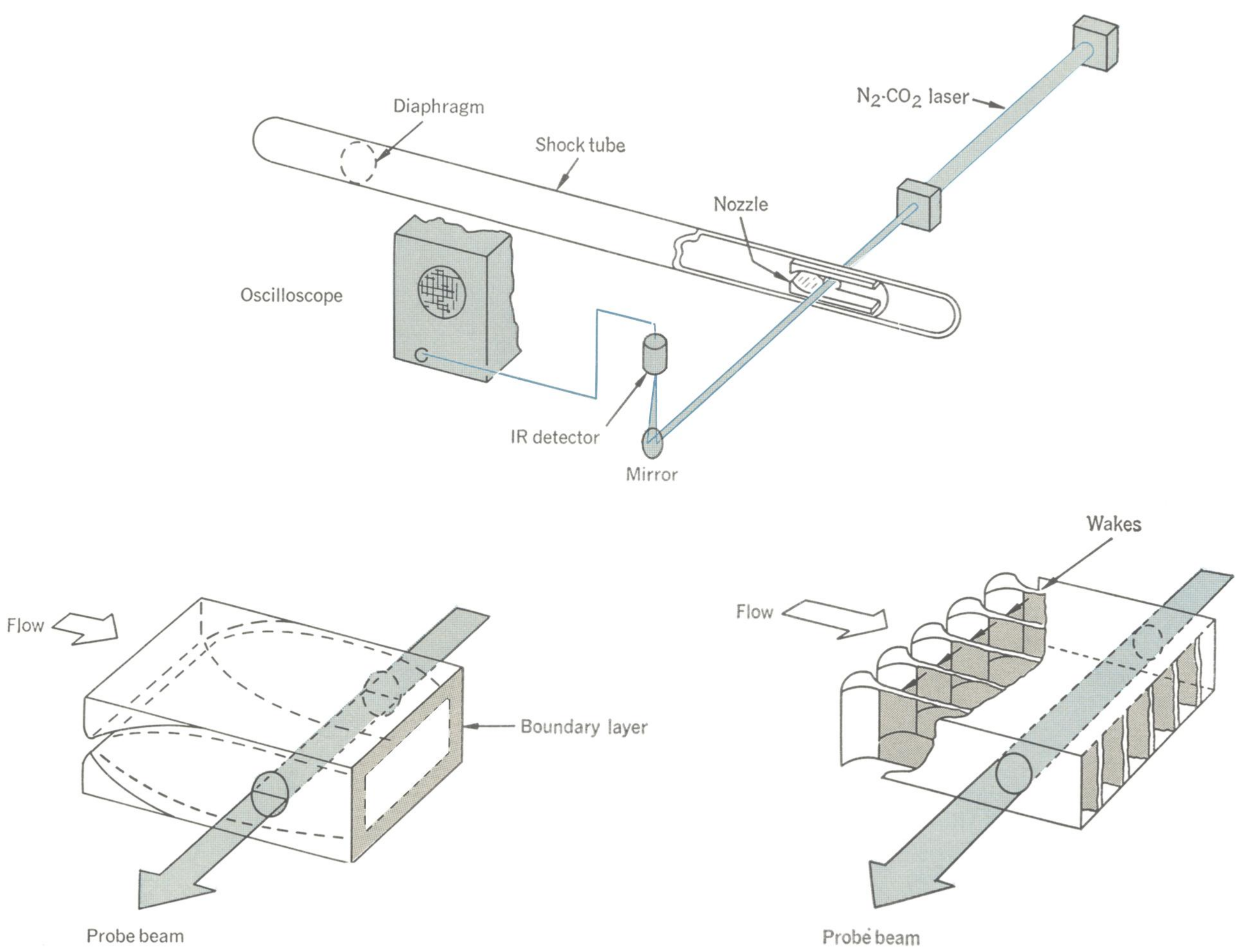
Consider what is required for efficient freezing of the upper-level vibrational energy. The maximum derivative of pressure and temperature in a supersonic flow tube occurs in the region of the throat area. Thus a typical characterizing parameter for allowable time for expansion past the throat is the ratio of the throat height to the gas velocity in the throat (which is just the speed of sound in the fluid). This flow time must be less than the effective relaxation time of the combined CO_2 and nitrogen upper laser level as it exists at the throat.† The effective relaxation time is dependent on both the temperature at the throat, and the fractional concentrations of CO_2 and water in the gas mixture; typically it is expressed in the form of a pressure–time product as it relates to gas temperature. Thus the effective time at the throat is this pressure–time product evaluated at the throat temperature divided by the static pressure (which is approximately half of the stagnation pressure) at the throat.

The effective time requirement leads to stipulations on the product of stagnation pressure and throat height in order to achieve efficient freezing of the available laser energy. For open-cycle combustion-driven systems, P_{stag} is generally fixed by conditions for diffuser-exhaust recovery to atmosphere. This relationship gives the throat

* $E_{max} = h\nu/[\exp(3380/T_{stag}) - 1]$ where h is Planck's constant, ν is the frequency, and T_{stag} is as in Fig. 4.

† That is, $H/U < (P\tau_{eff})_{T^*}/P^* \approx (P\tau_{eff})_{T^*}/0.5\,P_{stag}$ or $P_{stag}H < 2(P\tau_{eff})_{T^*}U$.

FIGURE 5. Shock-tube experiment to measure gain in an expanded N_2-CO_2 mixture. The gain-measuring apparatus outlined is said to be the most useful for ascertaining population inversion—distinction among gains of only a few percent being possible. Both single and array nozzles have been evaluated in the shock tunnel.



height as a function of CO_2 concentration and throat temperature. A downstream-to-throat-area ratio must be chosen sufficiently large that when the lower laser level has a population characteristic of the gas temperature downstream of the nozzle, its population is considerably less than the upper-level population.

In the cavity region, most of the available laser energy is stored in nitrogen. Since the energy is removed by laser action in CO_2, sufficient cavity length must be allowed for transfer of the energy stored in nitrogen vibration to CO_2. This length is simply the relaxation time for nitrogen's energy to transfer to CO_2 multiplied by the downstream flow velocity, and is inversely proportional to the concentration ψ of CO_2 in the gas mixture. Note that this is the minimum cavity length.‡ Generally the cavity must be longer, as energy removal also is limited by removal of lower-state energy by collisions with water or helium and, in most practical cases, by the allowable intracavity radiation flux.

In most gasdynamic lasers, laser-energy removal from the gas is flux-limited rather than kinetics-limited. It is important to note here that apart from vibrational deactivation, which occurs slowly downstream of the nozzle, energy not removed from the gas at a given point upstream is still available for removal downstream of that point and thus some flexibility in the design of optical cavities is possible.

Downstream, when an optical cavity is present, the rate at which quanta are generated in the cavity is equal to $G\varphi/h\nu$ quanta/cm^3/s, where G is the local gain coefficient in cm^{-1}, φ is the optical flux in W/cm^2, and h is Planck's constant. To compute the power output of an optical cavity, φ is adjusted until the average gain of the cavity equals the total cavity loss.

Two basic versions tested

Several different gasdynamic laser devices have been operated at various facilities. These include various configurations based on shock-tube-generation and combustion-powered devices. The performance of both types of equipment are comparable—for comparable configurations—as expected. Figure 5 shows a shock-tube device together with instrumentation. Figure 6 is a schematic of a combustion-powered, 1.4-kg/s device, concerning which some details follow.

The burner is round in cross section with a 15-cm-diameter flow area and a length in the flow direction of the order of 45 cm. It joins a conical mixing chamber, also approximately 45 cm long, which expands the flow cross section to 30-cm diameter. Both cyanogen (C_2N_2) and carbon monoxide have been used as fuels in this device. The fuel is burned with air at the back plate of the burner and ignition is maintained by a methane pilot burner, which also supplies part of the water in the flow. Additional nitrogen is injected midway between the burner and the mixing chamber to provide the right gas mixture and the proper temperature.

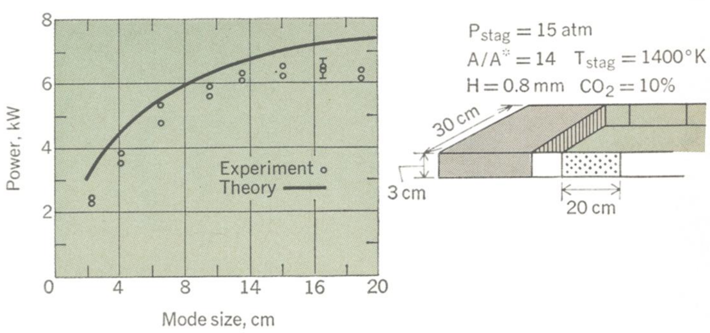
An array, 3 cm by 30 cm in cross section, consisting of nozzles containing an 0.8-mm-high throat (area ratio = 14), separates the burner from the cavity. In the cavity region, power is extracted by the use of a multihole-coupled multimode stable resonator, or by a mode-controlled unstable resonator. The former is shown in Fig. 6(A). The diffuser, which is downstream of the cavity, slows the 0.1-atmosphere Mach 4 flow to a low Mach number and raises the pressure in excess of one atmosphere so as to exhaust without pumping.

By use of the operating conditions given in Fig. 6(B), a power output of 6 kW was obtained for an operating time of 10 seconds. (The burner and nozzle row were water-cooled for steady-state operation. However, for simplicity, the cavity and diffuser, as well as the mirrors, were "heat sinked," limiting run time to the order of seconds.) Figure 7 shows the device.

Under operating conditions of the run, which produced 6 kW, the ideal laser power would have been 40 kW if complete freezing of the upper-state vibrational energy at the stagnation temperature were achieved together with 100 percent efficient energy extraction downstream. This power is a function, as discussed earlier, of the stagnation temperature and the Mach number (M). But as long as the Mach number is high enough that the lower state is well out of the way, power is relatively independent of M.

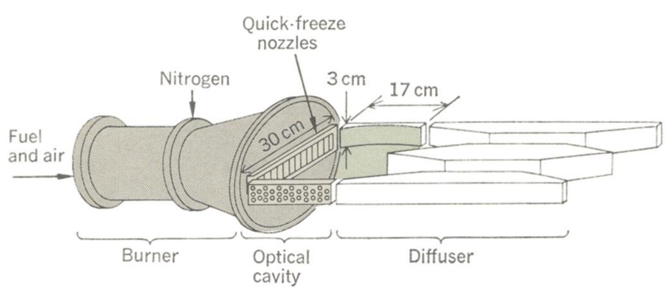
As the nozzle is not 100 percent efficient, 17.3 kW are lost to vibrational deactivation within the nozzle. This loss is a function of gas composition and the geometry of the nozzle.

FIGURE 6. A—Schematic of shock-tube-powered 1.4-kg/s gasdynamic laser and power measurements as a function of mode size. B—Exposition of combustion apparatus.



A

B



Typical Operating Conditions		Performance	
Stagnation pressure	17 atm	Power output	6 kW
Stagnation temperature	1300°K	Intracavity flux	1 kW/cm
Mach number	4.0		
Gas composition			
Carbon dioxide	8. %		
Carbon monoxide	0.2%		
Nitrogen	91. %		
Water	0.8%		
Mirror coupling	2. %		

‡ $L_{cavity\ min} > (P\tau_{transfer})_T\ U/P\psi_{CO_2}$ when the flux in the cavity tends to infinity.

Boundary layers on the walls of the nozzle subtract an additional 2 kW from the available laser power. (This loss would increase whereas the incomplete freezing loss would decrease if the nozzle size were smaller.)

Because the cavity was located somewhat downstream of the nozzle exit, some collisional deactivation, accounting for a loss of 1.2 kW, occurred before the gas entered the cavity.

In addition, 2 kW were lost within the cavity.

All of these losses are controlled by gas composition, Mach number, and the location of the cavity as well as—in the case of deactivation within the cavity—by the laser flux.

Mirror losses accounted for a 10.9-kW loss, largely due to the low coupling fraction used in these experiments—2.0 percent. The copper mirrors used in the tests have a combined absorption and scattering loss on reflection of the order of 1.5 to 2 percent. Mirror loss is controlled by reflectivity, the configuration of the resonator, output coupling, and the cavity flux. The mirror in these tests had an active length in the flow direction of 20 cm. Because of incomplete extraction while passing through the cavity, there was still 1.5 kW of laser energy in the gas.

These losses total 34.9 kW, leaving a net calculated laser output power of approximately 5.1 kW, which is reasonably consistent with the measured laser power of 6 kW. The largest uncertainty is in the mirror losses.

Two points should be made with regard to laser losses: (1) The aerodynamic and kinetic processes associated with gasdynamic laser operation are now relatively well understood, and fairly accurate predictions of device performance can be made. (2) Considerable improvement in the efficiency of gasdynamic lasers can be made by improving the tradeoffs between the listed losses in order to attain a higher fraction of the ideal laser power.

Mode control in gasdynamic lasers

Since the optical cavity that exists for a gasdynamic laser is basically short and fat, geometrical angles (defined by the ratio of the cavity height to the mirror spacings) are large compared with diffraction angles (defined by the ratio of the wavelength to the cavity height). The gasdynamic laser-cavity geometry, therefore, has an intrinsically high Fresnel number. With a large combustion-powered gasdynamic laser device, the ratio of geometrical angles to diffraction angles—based on the cavity size—is of the order of a thousand; i.e., the Fresnel number is of the order of a thousand.

Figure 8 shows possible schemes for obtaining near-diffraction-limited beam outputs. The stable resonator [8(A)] is the one most commonly used in ordinary gas lasers for achieving single-mode operation. ("Stable" here refers to geometrically stable, meaning that, from geometric optical considerations, off-axis rays within certain angular limits stay in the cavity. Losses from the cavity occur only by coupling through the mirrors or by diffraction.) In order to achieve diffraction-limited

FIGURE 7. Device diagrammed in Fig. 6(B).

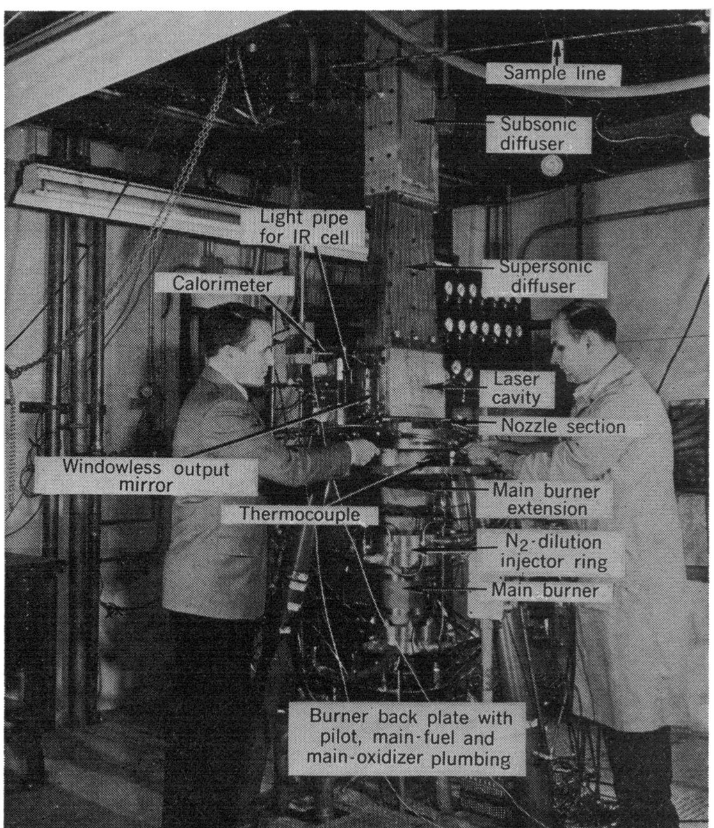
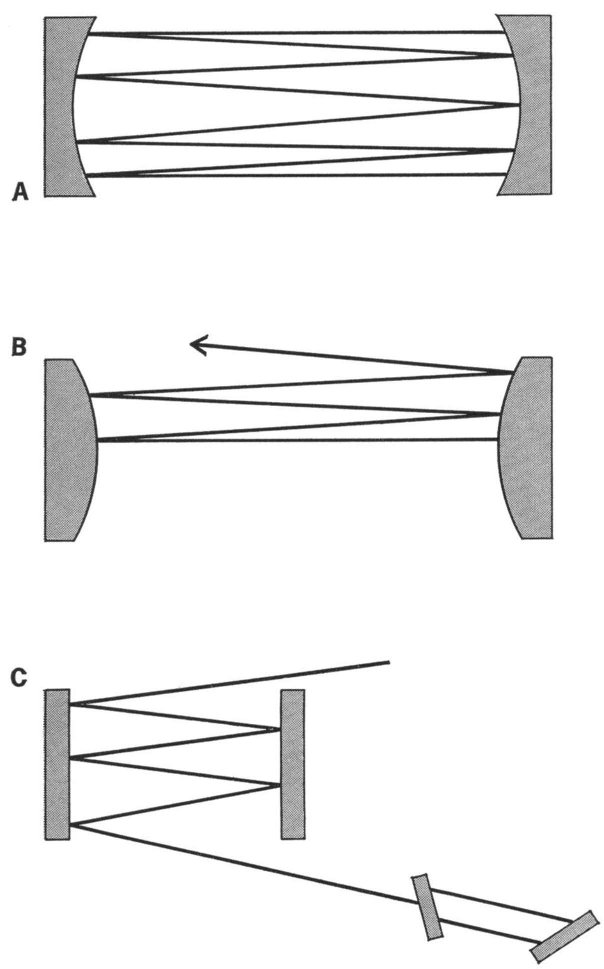


FIGURE 8. Mode-control schemes.



output (that is, minimum divergence consistent with wave optics), the stable resonator generally requires a low Fresnel number of the order of unity. Operated in this fashion, mirror-alignment requirements are less severe than for other types of resonators. In order to use this type of resonator in the high intrinsic Fresnel number medium of the gasdynamic laser, a large number of folds within the medium are required. Although this can be done, it does not appear to be the most advantageous approach to mode control in the gasdynamic laser.

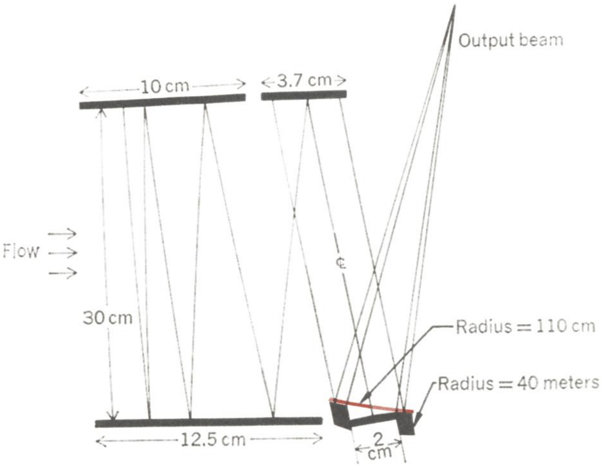
A second type of resonator is the unstable resonator,[30] in which, from geometric optical considerations, off-axis rays "walk out" of the cavity. These resonators, in principle, can operate in a lowest-order mode at any Fresnel number. They are easiest to operate when high total gain exists in the cavity so that the coupling fraction over the edge of the mirror can be large. Mirror alignment requirements are severe and are similar to those for the plane-parallel resonator. Unstable resonators appear promising for use with gasdynamic lasers, as experiments with an unstable resonator in a large combustion-driven device have shown. See Fig. 8(B).

Another approach to achieving diffraction-limited output from a gasdynamic laser is to use the master oscillator–power amplifier setup [Fig.8(C)], where the output of a low-power mode-controlled CO_2 laser is amplified by folding the beam through the gasdynamic laser using a mirror system. This system can also operate with the beam-folding geometry in the gasdynamic laser having Fresnel numbers considerably greater than unity. Alignment requirements again are severe and comparable to those for the unstable resonator. The advantage of the master oscillator–power amplifier approach is that frequency control and wavelength selection can be accomplished with the gasdynamic laser by control of these parameters in the driver oscillator.

Results were obtained with an unstable resonator (see Fig. 9) used with the combustion-driven laser. The beam path of the resonator is folded several times to increase the total gain of the system. (The plane of the folding is parallel to the flow direction.) The resonator consists of three flat mirrors and one small convex coupling mirror covering 35 percent of the area of the folded beam. The output is coupled out of the resonator over the edge of the convex coupling mirror to the outside world.

In the instance of a combustion-powered device, this output is picked up by a concentric concave mirror tilted at an angle to the system and focused out through a downstream hole so that flow disturbances introduced by entering air do not affect the optical quality of the medium. (Nor does the amount of flow exiting through the hole disturb the operation of the diffuser.) This hole location is a convenient way of circumventing the problem of suitably placing a window to handle the output

FIGURE 9. An unstable resonator. The output is coupled over the edge of the convex (40-meter-radius) mirror.



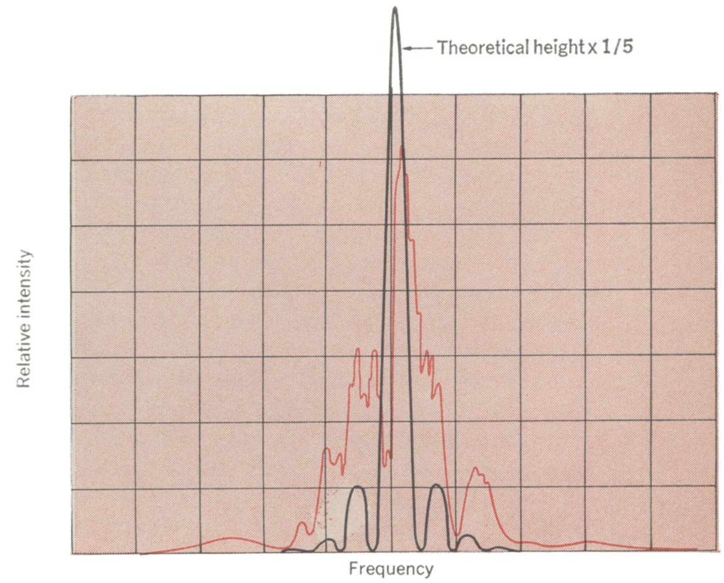
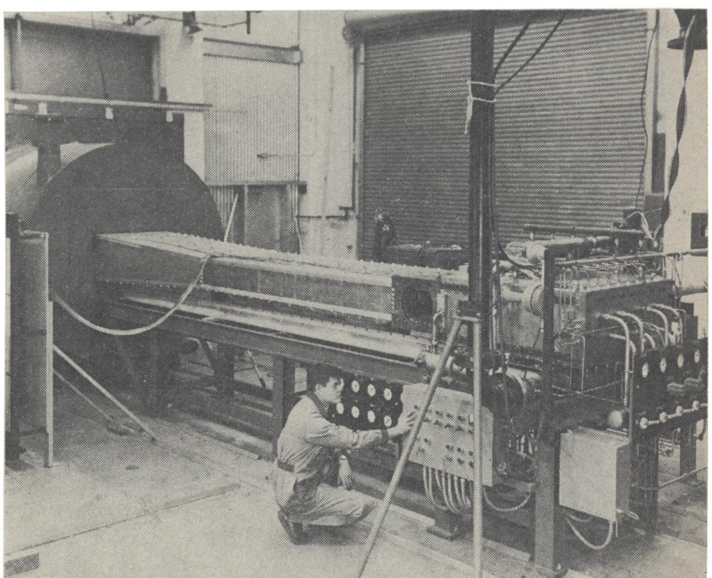


FIGURE 10. Results using an unstable resonator. Black line represents measured output power (of the order of 2 kW) whereas the colored line represents the theoretical far-field intensity distribution for an unstable resonator at 65 percent coupling operating in the lowest-order mode.

FIGURE 11. A recently constructed 14-kg/s gasdynamic device.



fluxes characteristic of a gasdynamic laser.

Under operating conditions similar to those for which 6 kW were produced in a multimode cavity, a power output of the order of 2 kW was achieved with the unstable resonator. Figure 10 shows IR scanner measurements. Also shown is the theoretical far-field intensity distribution for an unstable resonator of 65 percent coupling operating in the lowest-order mode. (The theoretical distribution has been multiplied by 0.2 to show it on the same scale as the output of the device.) This illustration indicates that the output radiance of the laser obtained under these operating conditions is approximately one sixth to one seventh that for pure lowest-order-mode operation, or, equivalently, about 2.5 times that for a diffraction-limited operation.

The mirrors used in these tests were copper and were operated in a heat-sink mode. Theoretical calculations indicate that significant distortion of these mirrors will take place during the run time and this distortion can lead to significant deviations from the ideal mode pattern.

In addition, in this device significant flow disturbances were present and these led to phase changes of a significant fraction of a wavelength across the beam cross section. Nozzle-array designs that eliminate or substantially reduce these flow disturbances have been developed. Also, water-cooled mirror structures that will not distort significantly under the heat loads of the gasdynamic laser have been developed. Although not conclusive, the results of these mode-control experiments on gasdynamic lasers seem to indicate that, with a uniform medium and with water-cooled mirrors, very near diffraction-limited performance of an unstable resonator can be achieved.

Finally, there are some fairly recent results to report about the large (approximately 14 kg/s) device shown in Fig. 11. This device, operated with CO as the fuel, has produced 60 kW of multimode power and 30 kW of near-diffraction-limited power in an unstable resonator, indicating the general scalability of these devices.

This work was supported in part by the Avco Corporation and in part by the Advanced Research Projects Agency and the U.S. Air Force.

REFERENCES

1. Wilson, J., "Nitrogen laser action in supersonic flow," *Appl. Phys. Letters*, vol. 8, pp. 159–161, Apr. 1966.

2. Patel, C. K. N., "Continuous wave laser action on vibrational-rotational-transitions of CO_2," *Phys. Rev.*, vol. 136, pp. A1187–A1193, Nov. 30, 1964.

3. Patel, C. K. N., "CW high power N_2-CO_2 laser," *Appl. Phys. Letters*, vol. 7, pp. 15–17, July 1, 1965.

4. Patel, C. K. N., "Selective excitation through vibrational energy transfer and optical maser action in N_2-CO_2," *Phys. Rev. Letters*, vol. 13, pp. 617–619, Nov. 23, 1964.

5. Patel, C. K. N., "CW high power CO_2-N_2-He laser," *Appl. Phys. Letters*, vol. 7, pp. 290–292, Dec. 1, 1965.

6. Sobolev, N. N., and Sokovikov, V. V., "CO_2 lasers," *Sov. Phys. Uspekhi*, vol. 10, pp. 153–170, Sept.–Oct. 1967.

7. Tiffany, W. B., Targ, R., and Foster, J. D., "Kilowatt CO_2 gas-transport laser," *Appl. Phys. Letters*, vol. 15, pp. 91–99, Aug. 1, 1969.

8. Osgood, R. M., Jr., and Eppers, W. C., Jr., "High power CO_2-H_2-He laser," *Appl. Phys. Letters*, vol. 13, pp. 409–411, Dec. 15, 1968.

9. Legay, F., "Study of a CO-N_2 laser by modulation method," *Compt. Rend. Acad. Sci. B.*, vol. 266, pp. 554–557, Feb. 26, 1968.

10. Walter, W. T., Piltch, M., Spilmene, N., and Gould, G., "Efficient pulse gas discharge laser," *IEEE J. Quantum Electronics*, vol. QE-2, pp. 474–479, Sept. 1966.

11. Leonard, D. A., "Theoretical description of 5106— a pulsed copper vapor laser," *IEEE J. Quantum Electronics*, vol. QE-3, pp. 380–381, Sept. 1967.

12. Leonard, D. A., "Saturation of the molecular nitrogen second positive laser transition," *Appl. Phys. Letters*, vol. 7, pp. 4–6, July 1, 1965.

13. Gerry, E. T., "Pulsed-molecular nitrogen laser theory," *Appl. Phys. Letters*, vol. 7, pp. 6–8, July 1, 1965.

14. Airey, J. R., "Cl + HBr pulsed chemical laser: a theoretical and experimental study," *J. Chem. Phys.*, vol. 52, pp. 156–157, Jan. 1, 1970.

15. Airey, J. R., "A supersonic mixing chemical laser," *Appl. Phys. Letters*, vol. 16, pp. 401–403, Dec. 15, 1969.

16. Spencer, D. J., Jacobs, T. A., Mirels, H., and Gross, R. W. F., "Continuous wave chemical laser," *Internat'l J. Chem. Kinetics*, vol. 1, pp. 493–494, Sept. 1969.

17. Spencer, D. J., Jacobs, T. J., Mirels, H., and Gross, R. W. F., "Preliminary performance of a CW chemical laser," *Appl. Phys. Letters*, vol. 16, pp. 235–237, Mar. 15, 1970.

18. Cool, T. A., Stephens, R. R., and Falk, T. J., "A continuous wave chemically excited CO_2 laser," *Internat'l J. Chem. Kinetics*, vol. 1, pp. 495–497, Sept. 1969.

19. Basov, N. G., and Oraevskii, A. N., "Attainment of negative temperatures by heating and cooling a system," *Sov. Phys. JETP*, vol. 17, pp. 1171–1174, Nov. 1963.

20. Kantrowitz, A. R., "Heat capacity lag in gas dynamics," *J. Chem. Phys.*, vol. 14, pp. 150–164, Mar. 1946.

21. Konyukhov, V. K., and Prokhorov, A. M., "Population inversion in adiabatic expansion of a gas mixture," *J. Exp. Theoret. Phys. Letters*, vol. 3, pp. 286–288, June 1, 1966.

22. Hurle, I. R., and Hertzberg, A., "Electronic population inversion by fluid-mechanical techniques," *Phys. Fluids*, pp. 1601–1607, Sept. 1965.

23. Herzberg, G., *Molecular Spectra and Molecular Structure*, 2nd. ed. I. *Spectra of Diatomic Molecules* (1950). II. *Infrared and Raman Spectra of Polyatomic Molecules* (1945). Princeton, N.J.: Van Nostrand.

24. Taylor, R. L., and Bitterman, S., "Survey of vibrational relaxation data for processes important in the CO_2-N_2 laser system," *Rev. Mod. Phys.*, vol. 41, pp. 26–47, Jan. 1969.

25. Rosser, W. A., Jr., Wood, A. D., and Gerry, E. T., "Deactivation of vibrationally excited carbon dioxide (ν_3) by collisions with carbon dioxide or nitrogen," *J. Chem. Phys.*, vol. 50, pp. 4996–5008, June 1, 1969.

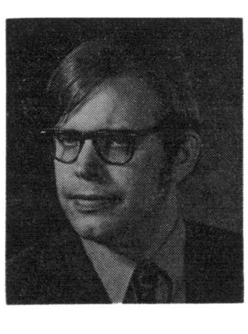
26. Sharma, R. D., and Brau, C. A., "Energy transfer in near resonance molecular collision due to long-range forces with application to transfer of vibrational energy from ν_3 mode of CO_2 to N_2," *J. Chem. Phys.*, vol. 50, pp. 924–930, Jan. 1969.

27. Herzfeld, K., "Deactivation of vibrations by collision in CO_2," *Disc. Faraday Soc.*, no. 33, pp. 22–27, 1962.

28. Herzfeld, K., "Deactivation of vibrations by collision in the presence of Fermi resonance," *J. Chem. Phys.*, vol. 47, pp. 743–752, July 15, 1967.

29. Rosser, W. A., Jr., and Gerry, E. T., "De-excitation of vibrationally excited CO_2^* (ν_3) by collisions with He, O_2, and H_2O," *J. Chem. Phys.*, vol. 51, pp. 2286–2287, Sept. 1, 1969.

30. Siegman, A. E., and Arrathoon, R., "Modes in unstable optical resonators and lens waveguides," *IEEE J. Quantum Electronics*, vol. QE-3, pp. 156–163, Apr. 1967.



Edward T. Gerry received the B.S. degree in physics from the College of William and Mary, the M.S. degree in engineering physics from Cornell University, and the Ph.D. degree from the Nuclear Engineering Department of the Massachusetts Institute of Technology. Much of his graduate research involved work with plasmas. At Avco Everett Research Laboratory, Everett, Mass., he previously was engaged in the development of high-temperature-plasma diagnostic techniques and in the study of dissipative processes in such plasmas. More recently, he has been studying population-inversion methods in gaseous-laser systems. The original work leading to the development of the CO_2 gasdynamic laser was led by Dr. Gerry. He is presently chairman of Avco's Laser Research Committee. Dr. Gerry is a member of the APS and the American Association for the Advancement of Science.