J. Indian Inst. Sci., Sept.–Oct. 1996, 76, 507–516.
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Gain measurements in a shock tube-driven gasdynamic laser

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Received on February 6, 1995; Revised on June 21, 1995.

Abstract

A shock tube-driven CO_2–N_2–He gasdynamic laser employing a two-dimensional wedge nozzle is described. The gain produced due to the expansion of the laser gas mixture compressed and heated due to the shock-wave propagation is measured using a weak probe signal at 10.6 μm for various gas mixture compositions and shock Mach numbers The expected optimum gain from this laser system is estimated using the gain optimization analysis presented here The variation on the measured small-signal gain shows a concordance matching trend with the predicted values for different gas compositions and system parameter combinations. A highest gain of 1.53 m^{-1} is achieved for the gas composition of CO_2:N_2:He = 11.5:50:38 5(%), reservoir pressure, 5.8 atm, and temperature 1218 K.

Keywords: Gasdynamic laser, shock waves, nozzle, small-signal gain.

1. Introduction

The idea of creating a population inversion in molecular systems by gasdynamic means was suggested, in its most general form, by Basov and Oraevski[1]. They suggested that the population inversions could be created by rapid heating or cooling of the molecular system. Applying this idea to a specific system of N_2–CO_2 mixtures, Konyukhov and Prokhorov[2] suggested that a population inversion could be achieved by rapid expansion of the mixture through a supersonic nozzle. A similar approach was suggested by Hurle and Hertzberg[3] for achieving an inversion in Xe. Ultimately, the first gasdynamic laser (GDL) was built in 1966 at AVCO Everett Research Laboratory using a gas mixture of CO_2-N_2-H_2O[4]. Presently GDLs are capable of producing nearly diffraction limited beams of power levels in the MW range[5].

Since the first demonstration in 1970, GDLs have been studied extensively and the salient features of these studies are summarised by Anderson[6] and Losev[7]. Lasing through gasdynamic means has been observed in many molecular systems including CO_2[4], N_2O[8], CO[9] and CS_2[10,11]. In addition to the oscillation at 10.6 μm CO_2, GDL lases at 9.4 and 16 μm which has many applications, such as laser isotope separation[12–18].

In general, the performance of a GDL is characterised through small-signal optical gain and optical output parameters. It has been established that the performance characteristics of a GDL depend on a large number of parameters like gas mixture composition, initial conditions (pressure P_0 and temperature T_0 at the reservoir), size and contour of the nozzle, etc. To choose optimal operating conditions for a GDL we must know how these parameters affect its characteristics. This is achieved theoretically by optimising the performance with respect to various system parameters such that the analysis enables the prediction of a combination of these parameters to yield an optimum value for small-signal optical gain. This type of gain optimization studies have been carried out extensively[19–28].

The aim of this paper is to present the experimentally measured optimum small-signal gain, in a shock tube-driven CO_2-N_2-He GDL, employing a two-dimensional wedge nozzle. The results are compared with the theoretically predicted optimum gain values based on similarity transformation technique[19]. Detailed description of the shock tube-driven GDL is presented before describing the technique employed to measure the small-signal gain. The gain optimization technique is also briefly described. The results are presented in the form of graphs.

2. Shock-tube-driven GDL

The basic principle of the GDL is to expand a hot laser gas mixture from a reservoir at high pressure through a supersonic nozzle to a high Mach number to achieve population inversion downstream of the nozzle. In the shock tube-driven GDL (Fig. 1) the reservoir conditions of high temperature and pressure are achieved by the propagation of a shock wave through the CO_2, N_2 and He gas mixture in the driven section of the shock tube. The shock tube is a stainless steel tube of internal diameter 0.165 m and wall thickness of 0.019 m. Thin-film platinum gauges mounted 50 cm apart on the tube are used to measure the shock speed while the piezoelectric pressure transducer mounted at the end of the tube is used to monitor the pressure developed in the laser gas mixture due to the passage of the shock. An 8-cm-wide two-dimensional convergent-divergent wedge nozzle of exit area ratio 128 with a throat height of 1 mm is inserted at the end of the driven section of the shock tube, as shown in Fig. 1. The design details of the nozzle are shown in Fig. 2.

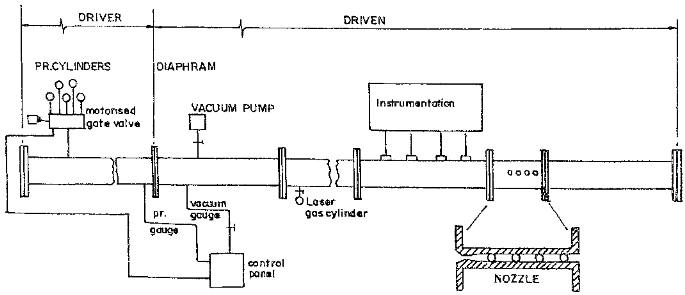

FIG. 1. Schematic diagram of shock tube-driven gasdynamic laser.

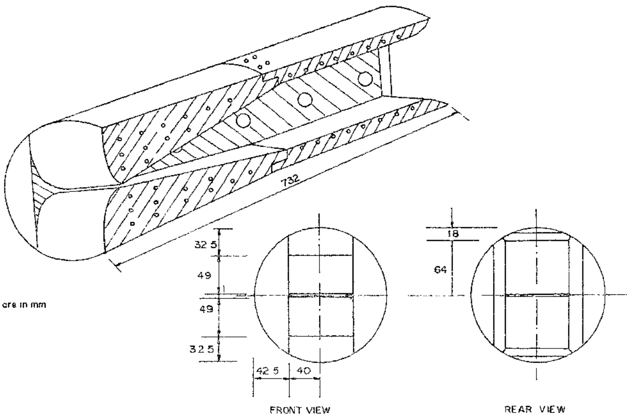

FIG. 2. Design details of the two-dimensional wedge nozzle.

Four observation ports with AR-coated ZnSe windows are provided for the gain measurements downstream of the nozzle throat. The small-signal gain of the laser is measured by passing a 10.6 μm probe beam of intensity I_0 from a waveguide CO_2 laser (Edinburgh Instruments Ltd) through the laser medium. The increase in the beam intensity ΔI_0 is measured using liquid nitrogen-cooled HgCdTe detector. The schematic diagram of the small-signal gain measurement setup is shown in Fig. 3. The data is acquired on multichannel transient recorders (Data Lab, UK) and processed on a minicomputer (HP).

The laser gain was measured at two ports situated in the expanding portion of the nozzle corresponding to the area ratio of 72 and 119 where the corresponding flow Mach numbers are 6.44 and 7.22, respectively. The output of the probe laser was tuned to $J = 20$ rotational line using a diffraction grating. The beam was prepositioned properly to account for the small fore-and-aft motion of the shock tube during the run. The transmitted laser beam (1.3 mm dia) was then spread out by striking a diffuse reflector so as to bathe the 1×1 mm active area of the detector with near uniform laser beam intensity. This permitted the detection of small changes in the laser signal (~ a few per cent) which were otherwise sensitive to tube vibration and beam deflection due to refraction caused by density gradients in the nozzle flow. The probe signal was chopped at 3 KHz frequency to provide the initial base line corresponding to the intensity I_0.

3. Theoretical analysis of the optimum gain

The expansion of the CO_2, N_2, and He gas mixture through the supersonic nozzle is governed by the usual mass, momentum and energy conservation equations and the equation

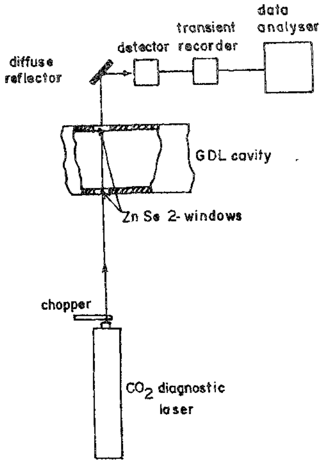

FIG.3. Schematic diagram of small-signal gain measurement arrangement in a gasdynamic laser.

of state. The vibrational energy exchange occurring through bimolecular collisions in the mixture, during expansion, is accounted for by considering an additional set of equations governing the relaxation of vibrational energy due to these collisions. Thus the fundamental governing equations for the GDL are[6],

$$\rho u A = \text{constant} \tag{1}$$

$$u du + dP/\rho = 0 \tag{2}$$

$$1/2\, u^2 + (1+\alpha)\, T + e_v = \text{constant} \tag{3}$$

$$P = \rho T \tag{4}$$

and

$$u\, d(e_v)_i/dx = (L'/u'_0\, \tau'_i)\, [(e_v)_e - (e_v)]_i, \quad i = \mathrm{I}, \mathrm{II} \tag{5}$$

where all the quantities except the primed ones are in nondimensional form. Here ρ, P, T and u are the density, pressure, temperature and velocity of the gas mixture, respectively. A is the local nozzle area ratio, L', the nozzle shape parameter, $\alpha = 2.5\, (X_C + X_N + 0.6\, X_H)$, τ'_i (i = I, II) are the effective vibrational relaxation times of simplified vibrational modes of the CO_2–N_2 system, respectively, with the corresponding specific vibrational energies.

$$(e_v)_I = X_C \{ \theta_1 [\exp(\theta_1/T_I)-1]^{-1} + 2\, \theta_2 [\exp(\theta_2/T_I)-1]^{-1} \} \tag{6}$$

$$(e_v)_{II} = X_C\ \theta_3 [\exp(\theta_3/T_{II})-1]^{-1} + (X_N/X_C)\ \theta_N [\exp(\theta_N/T_{II})-1]^{-1} \} \tag{7}$$

where $\theta_i (i = 1, 2, 3)$ are the characteristic vibrational temperatures of three vibrational modes of CO_2 molecule, θ_N, the corresponding value for the vibrational mode of N_2 molecule, T_I and T_{II} are the effective vibrational temperatures of modes I and II, and X_C, X_N and X_H are the mole fractions of CO_2, N_2 and He gases, respectively.

Following the method developed earlier,[21] eqns (1)–(5) are reduced to a universal form such that the solutions depend on a single universal parameter χ_I which combines all the other parameters of the system. The reduced equations in the universal form are,

$$\psi - \alpha\, d\psi/d\xi - X_C\, [G_I\, d\phi_I/d\xi + G_{II}\, d\phi_{II}/d\xi] = 0 \tag{8}$$

$$d\psi_I/d\xi = (K_I \psi/N_s) \exp [\chi_I + \xi(1-1/ij) - 2.739\psi^{-1/3}]\, [(E_e-E)/G]_I \tag{9}$$

$$d\phi_{II}/d\xi = (K_{II}\psi/N_s) \exp [\chi_I + 6.46\ \xi(1\text{-}1/ij) - 14.31\psi^{-1/3}]\, [(E_e\text{-}E)/G]_{II} \tag{10}$$

where ψ and ϕ_I and ϕ_{II} are the normalised (with respect to θ_N) translational temperature and the vibrational temperatures of modes I and II, respectively. The definition of the other terms is as in Reddy and Shanmugasundaram[21].

The universal parameter χ_I is defined as,

$$\chi_I = \ln\left\{\left[P_0' L' \theta_N' (\rho_* u_*)^{8.2}\right] \Big/ \left[(R_m')^{1/2} (T_0')^{3/2} (1.555 \times 10^{-8})\right]\right. \tag{11}$$

where the values $i = j = 1$ stand for wedge nozzle, and

$$\rho\ u\ = 0.686\text{–}8.0 \times 10^{-6}\ T_0'. \tag{12}$$

Thus χ_I can be computed for each run of the GDL by using the measured values of P_0' as here and T_0' (P_5 and T_5). The governing equations can be solved for ψ, ϕ_I and ϕ_{II} as functions of the independent variable ξ, which varies along the nozzle axis, at prescribed values of χ_I. These solutions are further used to compute the small-signal gain using the following relation

$$G_0/m = 9.77\ [\exp(\text{-}\theta_3/\phi_{II}) - \exp(-\theta_1/\phi_I)]\ \exp(-0.0703/\psi)\{Q_{vib}P(X_i)\ \psi^{3/2}\}^{-1} \tag{13}$$

where Q_{vib} is the vibrational partition function of the CO_2 molecule, $\theta_1' = \theta_1' / \theta_N'$ and $P(X_i)$ is given by,

$$P(X_i) = 1 + 0.7589\ X_N/X_C + 0.6972\ X_H/X_C. \tag{14}$$

For any given gas mixture of CO_2, N_2 and He, eqns (8)–(10) are solved simultaneously using the modified fourth-order R–K–G method. A typical variation of the flow

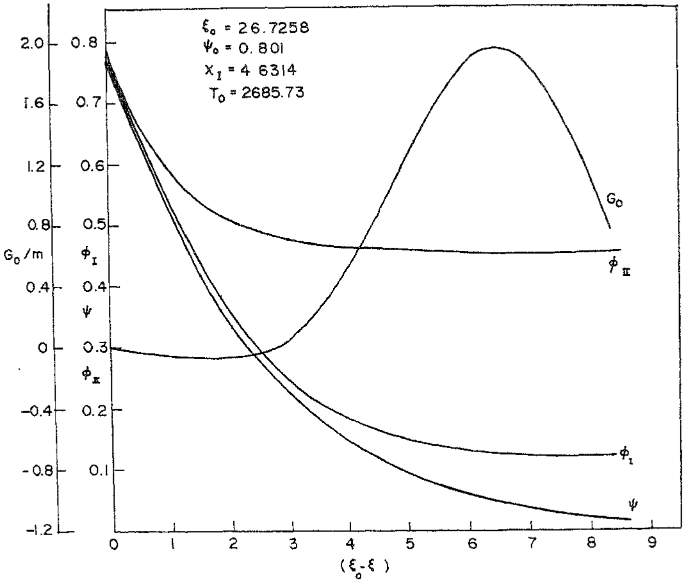

FIG. 4. Variation of the temperatures and the small-signal gain along the nozzle axis.

quantities ψ, ϕ_I and ϕ_{II} is shown in Fig. 4 along with the small-signal gain G_0 obtained from these equations. These results clearly indicate the early freezing of the vibrational temperature of the upper laser level while that of the lower level follows closely the translational temperature along the nozzle axis, thus resulting in the creation of population inversion leading to a positive small-signal gain which shows a peak value which occurs at a small distance downstream of the nozzle throat.

4. Results and discussion

The aluminium diaphragm separating the driver and the driven sections and the thin paper diaphragm separating the driven section and the nozzle-dump tank assembly are inserted before starting the experiment. Care is taken to clean the aluminium diaphragm thoroughly such that all the aluminium particles which are produced during the groove cutting are removed completely. The driven section and the dump tank are evacuated to a very low pressure ~0.1 torr. The driven section of the tube is then filled with the mixture of CO_2, N_2 and He gases in the known ratio up to a typical pressure ~100 torr. The driver section of the shock tube is then pressurised by feeding room-temperature He gas at high mass flow rate from high-pressure cylinders. The pressure difference across the diaphragm ruptures it instantaneously creating a shock wave which propagates into the laser gas mixture.

The pressure behind the reflected shock wave, the shock Mach number, and the small-signal gain was measured for various gas mixtures. The corresponding universal parameter χ_l for each gain measurement was calculated using the measured flow quantities in eqn (11). To ensure that the probe signal amplification was only due to population inversion in the CO_2 gas a few measurements were made with pure N_2 gas in the driven section. In all these measurements no positive gain values were obtained which confirmed the general integrity of the gain measurements. The variation of measured small-signal gain values with the universal parameter for various gas mixture compositions is presented in Figs 5–8 along with the theoretically estimated optimum gain values. It is seen that appreciable gain values are obtained for all the gas mixture compositions and the highest value of 1.53 m^{-1} is obtained for the composition CO_2:N_2:He = 11.5 : 50 : 38.5(%) with the reservoir pressure and temperature of 5.8 atm and 1218 K, respectively. In addition, the experimental values match well with the predicted values. However; it is seen that the measured gain values do not match the corresponding optimum values estimated from the theory presented here. This mismatch may be due to the following reasons. The small-signal gain (eqn. (13)) is derived assuming Lorentzian line shape due to collision broadening. However, at very low pressures as found in the GDL cavity situated downstream of the nozzle throat, the line shape is dominated by both collision and Doppler broadening. Thus the gain equation should be suitably modified assuming Voigt function for the line shape[23]. This may reduce the predicted gain

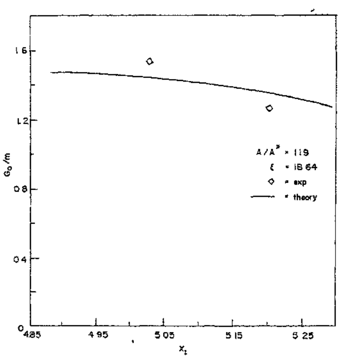

Fig. 5 Variation of small-signal gain with the universal parameter χ_l for the composition CO_2:N_2:He= 11.5:50:38.5(%).

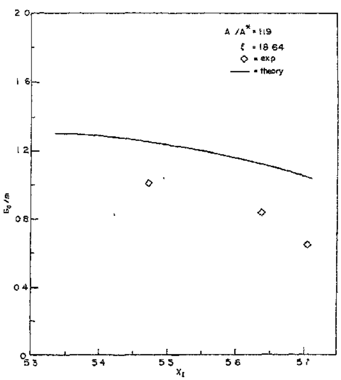

FIG. 6. Variation of small-signal gain with the universal parameter χ_l for the composition CO_2.N_2:He= 12:49:39(%).

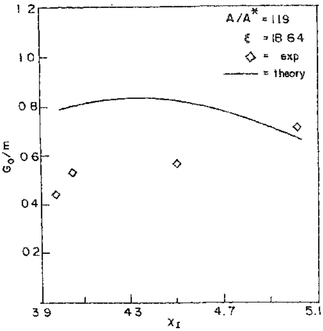

FIG 7. Variation of small-signal gain with the universal parameter χ_I for the composition CO_2:N_2:He= 15:25:60(%).

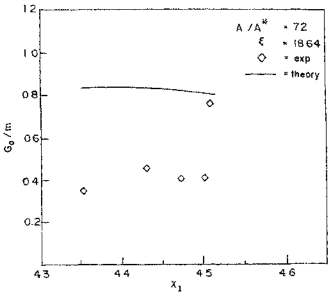

FIG. 8. Variation of small-signal gain with the universal parameter χ_I for the composition CO_2:N_2:He= 15.25.60(%) at different locations in the nozzle

values up to 30%, as shown in Shanmugasundaram and Reddy[23], thus reducing the difference between the measured and the predicted values noticed in Figs 5–8. In addition, the differences may also be due to the jumping of the probe laser wavelength to different rotational quantum numbers and uncertainties in the measurement of laser gas mixture compositions. The agreement can be improved by eliminating these discrepancies.

5. Conclusions

The design and fabrication of a shock tube-driven CO_2-N_2-He GDL operating at 10.6 μm is described in detail. The laser employs a two-dimensional wedge nozzle to achieve population inversion. The small-signal gain values are measured for different gas mixture compositions using a very low-power probe signal from a CO_2 waveguide laser. Highest small-signal gain of 1.53 m^{-1} is obtained for the mixture composition of CO_2: N_2: He = 11.5: 50: 38.5(%) for the reservoir pressure and temperatures of 5.8 atm and 1218 K, respectively. Theoretical analysis of the gain optimization in GDLs is described based on the similarity transformation technique. The experimental results are compared with the theoretical gain values for various gas compositions. The measured gain values exhibit variation similar to predicted values.

The measured performance of the laser is not matching well with the corresponding predicted optimum performance. This mismatch can be eliminated by incorporating line broadening effects in the analysis and also by using a probe laser tunable over different rotational lines. A simple power estimation shows that a peak power of ~0.34 kW can be obtained from the GDL at 10.6 μm using an output coupler of 95% reflectivity.

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