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Design and operation characteristics of a high power transverse flow pulser sustained cw CO_2 laser

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Abstract. A transverse flow, transverse discharge cw CO_2 laser in which dc discharge is sustained by employing high repetition rate high voltage pulses has been developed. Pulser sustained discharge through electrodes of innovative design provided uniform excitation at electrical input power densities more than 10 W/cc. Laser output power more than 2·5 kW was obtained in a laser gas mixture consisting of 0·5 mbar of CO_2, 16 mbar of N_2 and 38·5 mbar of He. Design details and operational characteristics of this laser are presented.

Keywords. CO_2 laser; transverse flow.

PACS Nos 42·55; 42·60

1. Introduction

High power cw CO_2 lasers are being increasingly used worldwide for various industrial applications such as welding, cutting, surface hardening and other material processings. In the development of a high power cw CO_2 laser there are two main problems. First is to establish and maintain uniform and stable electrical discharge in large gas volumes at high electrical input power densities and the second is to remove the remaining heat from the laser gas mixture after extracting the laser power. cw CO_2 lasers have normally 10–20% electro-optic efficiency, thus about 90–80% of total electrical input power gets dissipated in laser gas raising its temperature. This waste heat has to be removed at a sufficiently fast rate before gas gets too much heated up to avoid thermal instability and bottlenecking.

In high power cw CO_2 lasers in the kilowatt range, the waste heat is usually removed by convective cooling i.e. circulating the laser gas mixture through the discharge and then through the heat exchanger in a closed loop configuration. Various discharge schemes have been developed for convective cooled high power cw CO_2 lasers, they can be classified into two types: fast axial flow longitudinal discharge lasers and transverse flow transverse discharge lasers. In the first type, the discharge electric field is applied along the resonator axis similar to the conventional diffusion-cooled CO_2 laser and the laser gas mixture is also flown axially at very high speeds in a turbulent manner which helps in maintaining uniform and stable discharge besides removing heat. In order to create fast turbulent flow through the long and narrow discharge tube, the blower must have very high pressure head and large volumetric flow capacity. Specially designed roots-blower or turbo-blowers are usually used for this purpose, which are very expensive with increasing capacity (Marten *et al* 1988). In transverse flow design the flow cross-section is relatively large and correspondingly the pressure drop across the discharge is low. Fast gas flow in transverse flow lasers can be obtained with the readily available axial or centrifugal blowers. Because of this, most of the multikilowatt cw CO_2 laser systems operating at power levels more than 10 kW have so far been developed on transverse flow transverse discharge concept (Merchant 1985; Spalding *et al* 1989; Tabata *et al* 1984). With respect to better laser beam quality which is often desirable for many material processing applications, the transverse flow shows density gradients across the resonator axis causing deflection and distortion of the phase front of the laser field. However this may be compensated by appropriate resonator design (Sona 1989).

In transverse flow lasers, some kind of auxiliary discharge is usually required in order to establish and maintain uniform and stable dc discharge in large gas volumes at high electrical input power densities. Various techniques such as electron beam (Fenstremacher 1972), rf discharge (Nicholas and Brandenerg 1972), silent corona discharge (Tabata *et al* 1984), high voltage high repetition rate pulser (Nath *et al* 1986; Reilly 1972) and auxiliary dc discharge (Noda *et al* 1989; Wu 1987) have been utilized for this purpose. Among these techniques the high voltage, high repetition rate pulser sustained discharge seems to be more attractive in which the dc discharge need not be self-sustained. This ensures better discharge stability, independent control of E/P (electric field/gas pressure), full operational power range, ease of modulation and stability of laser power (Nath *et al* 1986). High power transverse flow cw CO_2 lasers based on this technique have been developed up to 20 kW output power level (Merchant 1985). However, the electrical input power density and the laser output power obtained in these laser systems were typically 2 W/cc and 0·3 W/cc respectively, much smaller than those obtained in other transverse flow lasers utilizing different excitation techniques (Spalding *et al* 1989). We have developed a transverse flow pulser sustained cw CO_2 laser utilizing specially designed electrodes which in combination with pulser ionization ensured very uniform and stable dc discharge at electrical input power loadings more than 10 W/cc. Laser power more than 2·5 kW was obtained in a gas mixture containing 0·5 mbar of CO_2, 16 mbar of N_2 and 38·5 mbar of He at a flow velocity of 40 m/s. The optimum laser gas mixture contained relatively high concentration of N_2 compared to earlier reported values in similar devices (Tabata *et al* 1984; Nath *et al* 1986). We present in this paper the design details and operational characteristics of this laser.

2. Laser constructional features

The main subsystems of the high power CO_2 laser are laser head, dc power supply, pulse preionizer, discharge electrodes, gas blower, heat exchangers, optical resonator, control panel, and vacuum and gas filling units. The laser head consisted of a cylindrical vacuum chamber of 2 m diameter and 1·5 m length with dished end doors constructed of mild steel. Figure 1 is a schematic diagram of the interior of the laser head which encompasses a pair of fluid resistance ballasted multi-tube anodes, a common cathode, a centrifugal blower, two large heat exchangers and a folded path optical resonator. The anode whose structure has been schematically shown in figure 2 consisted of 100 elements formed from 304 ss tubes of 4 mm od and 2·5 mm id. All tubes were bent

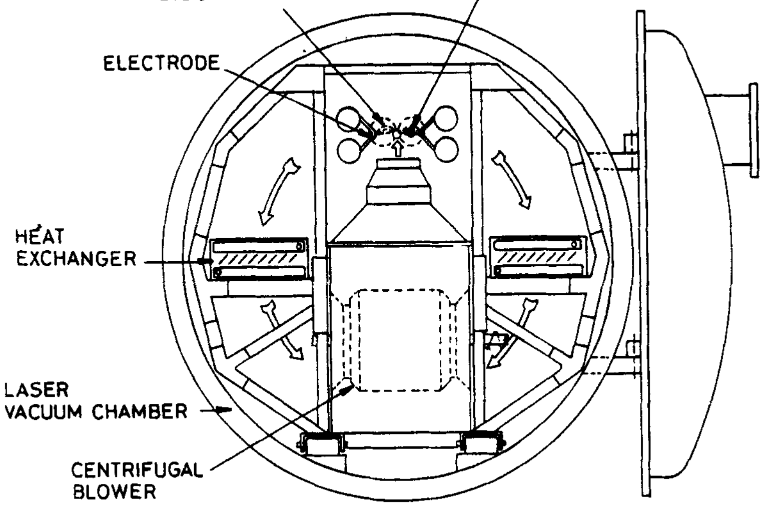

Figure 1. Schematic diagram of 2·5 kW transverse flow cw CO_2 laser.

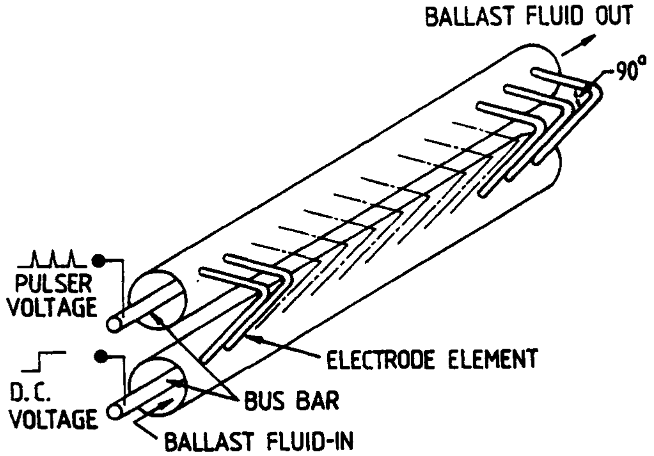

Figure 2. Schematic diagram of discharge electrode.

by 90° at the middle and their two open ends were inserted in two fibre glass epoxy tubes of 100 mm od and 70 mm id, and 1·2 m length. The separation between two consecutive elements was 10 mm. The vertex, i.e. bent portion of each tube mainly participated in the gas discharge. The ballast fluid solution which was prepared by dissolving suitable amount of potassium carbonate in distilled water was recirculated through the lower and upper epoxy tubes and each electrode element. Bus-bars made of 304 ss rod of 6 mm diameter and 1·2 m length were placed in each epoxy tube opposite to the tips of electrode elements. DC and pulser voltages were applied on separate bus-bars. The fluid column between bus-bar and tips of electrode elements worked as the ballast resistance. The ballast resistance for dc and pulser current could be independently adjusted by changing the distance between bus-bar and tips of electrode elements. Since ballast fluid was passing through all electrode elements it

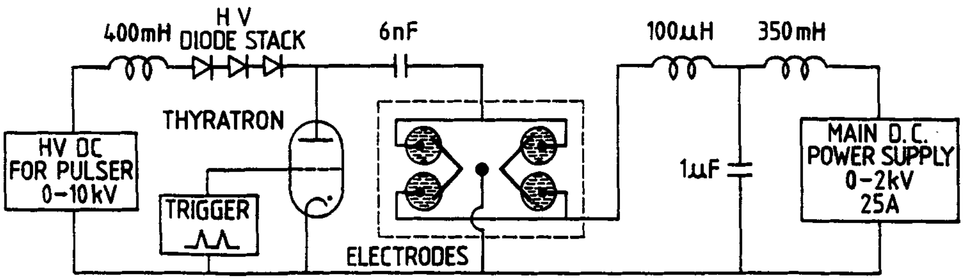

Figure 3. Electrical schematic of pulser and main discharge.

ensured their efficient cooling during operating condition. The impedance of ballast fluid was so adjusted that the electrical power dissipated in it was within 30% of the total electrical input power. The cathode common to both anodes was formed with a water-cooled copper tube of 12·5 mm od and was placed between them at an equal distance of 35 mm. A pair of active regions each of 100 cm length was produced between these electrodes. The laser gas was circulated through discharge region and heat exchanger with the help of a commercially available double entry centrifugal blower which was suitably modified for operation at low pressures typical of laser operating condition. In order to obtain uniform gas flow through both discharge regions each having 100 × 3·5 cm aperture, a duct with adjustable vanes was placed at the outlet of the centrifugal blower. Uniform gas flow velocity of 40 ± 2 m/s was obtained at 3000 rpm blower speed. All measurements were done at this flow condition. The heat exchangers designed for removing 25 kW of total heat from the laser gas were made of finned tubes. While designing, the number of staggered rows of fin tubes and the interfin separation were optimized to get minimum pressure drop across the heat exchanger. The electrical circuit including pulser developed for this laser is schematically shown in figure 3. The main discharge current was provided from a variac controlled dc power supply of 0–2 kV, 25 A maximum current rating. The pulser unit was having basically a high frequency capacitor charging and fast discharging circuit. A 6 nf capacitor was inductively charged up to 15 kV and discharged using a hydrogen thyratron as a switching element at repetition rates up to 7·5 kHz. Typical rise time and width at half maximum of the pulse voltage were 100 ns and 300 ns respectively. The laser power was extracted from both active regions in a single beam using a U-folded stable optical resonator formed by means of a 98% reflecting molybdenum concave mirror of 20 m radius of curvature, a pair of gold coated plane mirrors placed at 90° with each other for beam folding and a ZnSe plane output coupling mirror of 40% transmitivity. All these mirrors were water cooled and were mounted on end doors of the laser chamber. The laser power was measured with water cooled laser power meter (Ophir make).

3. Laser operational characteristics

The laser vacuum chamber was first evacuated below 0·5 mbar (measured on a Bourdon type gauge) with the help of a double stage rotary pump of 4000 lpm capacity and then filled with required amount of CO_2, N_2 and He gases. After switching on water through heat exchangers, cathode and mirrors; ballast fluid through anodes, and the centrifugal blower, the pulser discharge was initiated at the desired repetition rate and voltage. The dc voltage was then superimposed on the pulser discharge and the laser power was extracted.

In order to maximize the laser output power, its dependence on different experimental parameters such as laser gas mixture, gas pressure, discharge current, pulser voltage and repetition rate was investigated. The V–I characteristics of the main discharge indicated positive impedance behaviour as observed in PIE CO_2 laser (Nath *et al* 1986) and CO_2 lasers with dc auxiliary discharge (Noda *et al* 1989; Wu 1987). The ultimate discharge current before the onset of discharge instability increased with the increase of pulser voltage and its repetition rate. However, the dc discharge voltage reduced, maintaining the ultimate input power loading into the discharge almost unchanged over a large variation in pulse power. Figures 4a and 4b show the ultimate input power and corresponding laser output power as a function of pulser voltage and its repetition rate respectively in a typical laser gas mixture. This observation indicates that the discharge volume has an instability threshold, consistent with the electrothermal instability criteria presented by Nighan (1974). Figure 5 shows the variation of laser power with the partial pressure of CO_2. It indicates that the maximum laser power could be obtained with CO_2 partial pressure within 1·0 mbar in laser gas mixtures containing CO_2, N_2 and He up to 55 mbar of total pressure. The discharge quality deteriorated beyond 2 mbar of CO_2 partial pressure and laser

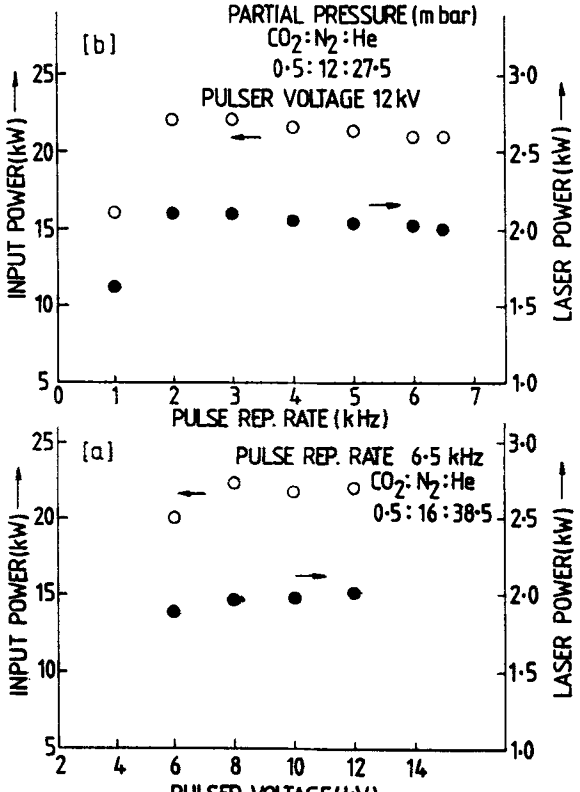

Figure 4. Effect of (a) pulser voltage and (b) its repetition rate on ultimate electrical input power and laser output power.

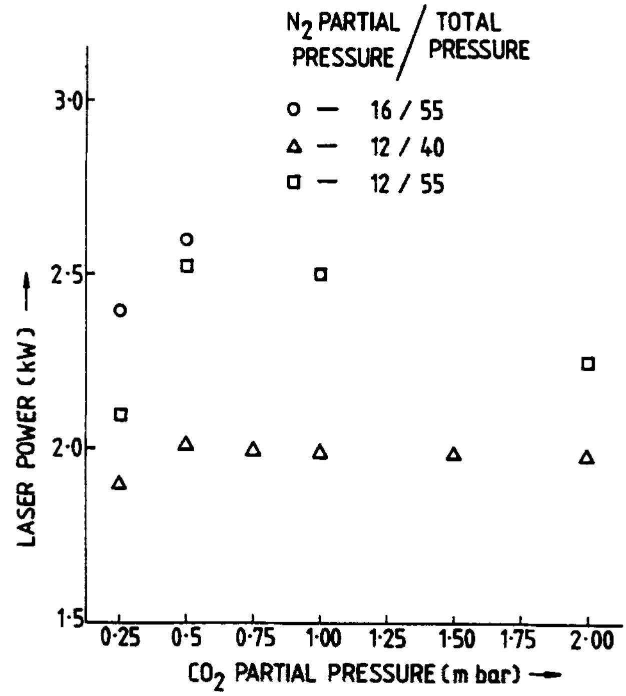

Figure 5. Effect of CO_2 partial pressure on laser power.

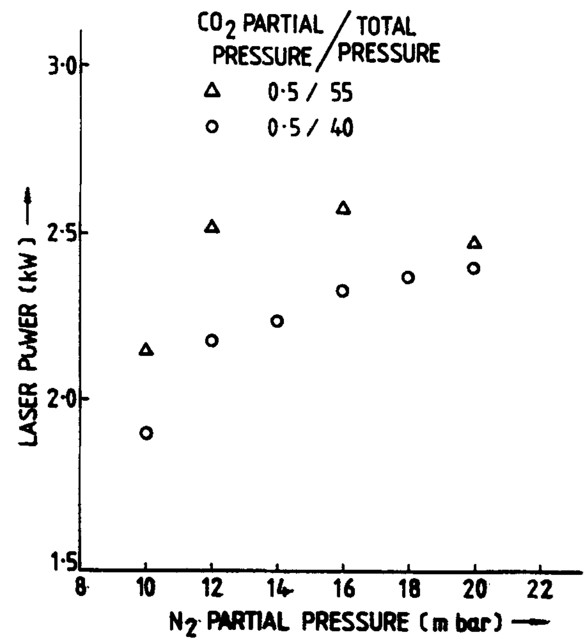

Figure 6. Effect of N_2 partial pressure on laser power.

power reduced. However, it increased substantially with the increase of partial pressure of N_2, as shown in figures 5 and 6. At a relatively lower total gas pressure typically 40 mbar, increase in laser power was monotonic, but at higher pressures (> 55 mbar), laser power had a peak at around 16 mbar of N_2 partial pressure. As observed with

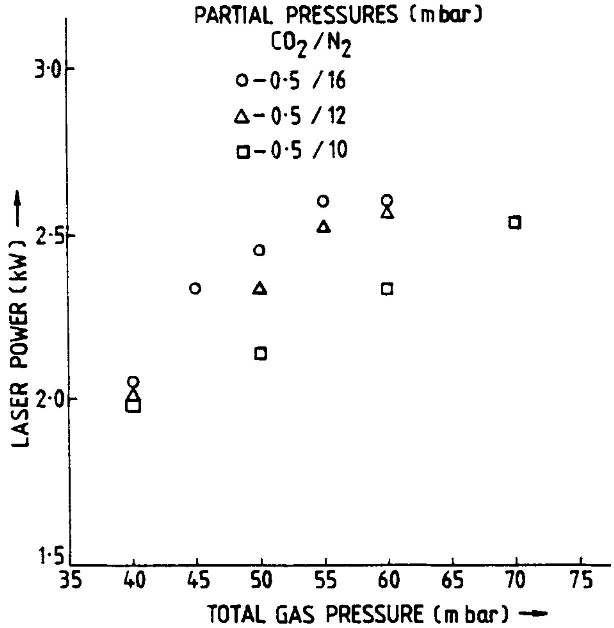

Figure 7. Effect of total gas pressure on laser power.

high partial pressure of CO_2, the discharge quality deteriorated reducing the laser power when N_2 partial pressure was increased beyond the optimum value. In order to study the effect of He pressure on laser power the total gas pressure was increased by adding more helium maintaining the partial pressures of CO_2 and N_2 constant in the mixtute. The variation in laser output power with the change of the total gas pressure is shown in figure 7. When the total gas pressure was increased by adding more helium the laser power increased and then tended to saturate. Maximum laser power of 2·7 kW was obtained in a laser gas mixture containing 0·5 mbar of CO_2, 16 mbar of N_2 and 38·5 mbar of He with 11% electro-optic efficiency. The maximum laser power was limited by the current capacity of the dc power supply. The laser beam was in multimode and was 30 mm in diameter. The beam divergence was estimated by measuring beam diameter at different distances from the laser head and it was approximately 2 mrad.

4. Discussion

Operational characteristics of the laser described above are almost similar to the observations recently reported for cw CO_2 lasers with dc auxiliary discharge (Noda *et al* 1989; Wu 1987) and earlier reported PIE CO_2 laser (Nath *et al* 1986). However, the electro-optic efficiency of 11% obtained in this laser is relatively small compared to earlier reported values (Noda *et al* 1989). It has been reported that the efficiency could increase with the increase of laser beam diameter (Noda *et al* 1989). With the present optical resonator the laser beam diameter was 30 mm and due to lack of optical components of different curvatures and reflectivities, the resonator parameters could not be optimized for maximizing laser output power. Substantial enhancement in laser output power is expected once optical resonator parameters are optimized since efficiencies in the range of 15–20% have normally been achieved in similar types of discharge configuration (Tabata *et al* 1984; Noda *et al* 1989). The ultimate input power density which was estimated to be about 12 W/cc is almost at the threshold limit of thermal instability (Marten *et al* 1989). Compared to PIE CO_2 laser this is substantially high owing to the modified electrode design used in the present system. The optimum gas composition had relatively less CO_2 concentration and high N_2 concentration compared to earlier reported values (Nath *et al* 1986; Tabata *et al* 1984; Wu 1987). Recently Kuzumoto *et al* (1989) have reported extremely high optimum molar fraction of N_2 in a transverse flow cw CO_2 laser excited by silent discharge and have attributed this to the increase of excitation efficiency with the increase of N_2 concentration. A rate equation model explaining our observations will be presented in the near future.

5. Conclusion

In conclusion, we have developed a transverse flow pulser sustained cw CO_2 laser utilizing mostly indigenous components and studied its operational characteristics. The laser performance was similar to those reported recently in literature. Laser output powers exceeding 2·5 kW were obtained in laser gas mixture containing relatively high N_2 partial pressure. This technology should be easily scalable up to much higher power levels. Based on this technology, CO_2 lasers up to 10 kW output power will be developed for industrial applications.

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