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A DC excited waveguide multibeam CO_2 laser using high frequency pre-ionization technique

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Abstract. High power industrial multibeam CO_2 lasers consist of a large number of closely packed parallel glass discharge tubes sharing a common plane parallel resonator. Every discharge tube forms an independent resonator. When discharge tubes of smaller diameter are used and the Fresnel number $N \ll 1$ for all resonators, they operate in waveguide mode. Waveguide modes have excellent discrimination of higher order modes. A DC excited waveguide multibeam CO_2 laser is reported having six glass discharge tubes. Simultaneous excitation of DC discharge in all sections is achieved by producing pre-ionization using an auxiliary high frequency pulsed discharge along with its other advantages. Maximum 170 W output power is obtained with all beams operating in EH_{11} waveguide mode. The specific power of 28 W/m is much higher as compared to similar AC excited waveguide multibeam CO_2 lasers. Theoretical analysis shows that all resonators of this laser will support only EH_{11} mode. This laser is successfully used for woodcutting.

Keywords. CO_2 laser; DC excitation; waveguide resonator; HF pre-ionization.

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1. Introduction

Output power of slow-flow diffusion cooled CO_2 lasers is limited to about 50 W/m of cooled discharge length, independent of tube diameter [1]. According to length scaling of laser power, such a laser of 1 kW output power would need about 20 m of cooled length, which is quite unwieldy. To overcome this limitation, for constructing such type of lasers of few kilowatts output power, multibeam technique is used [2]. Multibeam CO_2 lasers consist of large number of closely packed parallel discharge tubes, sharing a common plane–plane resonator. All beams of a multibeam CO_2 laser are to be focused to get total power in the focal spot. Multibeam CO_2 lasers of multi-kilowatt range with laser head of only 2–3 m are constructed for many industrial applications [3]. All discharge tubes of such a laser are independent resonators and different beams have no phase relation. These lasers are suitable particularly for surface hardening, surface melting, cladding etc. where large beam spots are required. Multibeam CO_2 lasers are gaining importance due to the possibility of phase locking of all beams, which can extend their applicability [3]. Number of discharge tubes and cooled discharge length of a multibeam laser have to be optimized to get the required power. Tubes of smaller diameter allows accommodating more number of tubes for a given diameter of plane resonator mirrors. Gaussian free space resonator mode propagation is not possible in discharge tubes of very small diameter [4]. Instead of open resonator Gaussian modes, waveguide modes are supported in such tubes. Waveguide resonator modes are superior to free space open resonator modes in many respects as discussed below.

Waveguide modes are supported in a laser resonator only when the Fresnel number $N = a^2/\lambda l \ll 1$, where $2a$ is the tube diameter, λ the laser wavelength and l the resonator length. Necessary details of the waveguide resonators and modes are discussed in [4–7]. Circular glass discharge tube waveguides support circularly symmetric EH_{1m} hybrid modes. Transverse intensity distribution of different EH_{1m} modes is shown in [6]. The lowest waveguide mode EH_{11} having conical intensity distribution resembles the free space Gaussian TEM_{00} mode of an open resonator. For circular resonators, pure EH_{11} mode can be approximated to the TEM_{00} beam of radius $w_0 = 0.6435a$, with power overlap of 98%. The most important property of the waveguide resonators is its strong discrimination of higher order EH_{1m} modes. For narrow tube diameters, except the lowest EH_{11} mode, higher order modes are suppressed due to their inefficient coupling from the resonator mirrors back into the waveguide. Reflections of propagating beam from walls of the waveguide resonators introduce absorption losses proportional to m^2/a^3, again resulting in discrimination of higher modes. For a typical waveguide CO_2 laser, the EH_{11} mode has round-trip loss of 2.6%, and next mode EH_{12} has 73% loss, providing excellent mode discrimination [7]. In homogeneously broadened CW gas lasers only EH_{11} mode is supported [4]. Gerlach *et al* [8] have discussed losses of EH_{11} and higher modes; exclusively for flat mirrors placed at small distances from the ends of waveguide CO_2 lasers. Stability of a plane–plane resonator is known to be very critical. Lasing with such resonator must cease entirely due to the slight misalignment of the output mirror. Antyukhov *et al* [9] have studied the effect of misalignment of mirrors on lasing action and modes of a waveguide CO_2 laser. They have shown experimentally that in a waveguide resonator, laser power is less critical to misalignment of plane resonator mirrors, which is an added advantage for multibeam lasers. Considering these advantages, we have developed a waveguide multibeam CO_2 laser using DC excitation along with high frequency (HF) auxiliary discharge for pre-ionization. A HF pulse discharge produces pre-ionization in all discharge tubes before the DC high voltage is applied. This technique solved the major problem of simultaneous excitation of DC discharge in all tubes, along with other advantages discussed further.

High-power multibeam waveguide CO_2 lasers using audio frequency (AC) excitations in 10 to 70 kHz range, using capacitive coupling have been constructed earlier [3,10,11]. In such excitation scheme, oil is used for cooling the discharge tubes and the foil electrodes. The oil coming out of the laser head is ultimately cooled by water, consuming more electrical power. Oil cooling is very inconvenient to handle, particularly in case of breakage of the fragile glass discharge tubes. Secondly, oil has much lower heat transfer coefficient compared to water. With the DC excitation, we could use chilled water for cooling discharge tubes and the cathode blocks. Water-cooling is more efficient, simple and cleaner when compared to the oil cooling. In DC excitation, around 30% electrical power is dissipated in the series ballast resistors and at least one electrode has to be introduced in the discharge tube. Even with these drawbacks of DC excitation, we have obtained almost double specific power (W/m) from our laser compared to the AC excited multibeam lasers, along with the major advantage of efficient water-cooling. This paper reports the construction and operation of our waveguide multibeam CO_2 laser.

2. Laser head

This laser has six discharge tubes of 1 m cooled discharge length divided in two equal parts for design and operational convenience. Such division of discharge length requires two high voltage anodes in the central region of each discharge tube to have electrically grounded common cathodes at the two extreme ends, for operational safety. There is no discharge between the inter anode space of all tubes. For such a design, single glass tubes of 1445 mm length were required. Glass tubes of 5 mm internal and 8 mm outer diameter were selected to have $N = 0.40$, satisfying the condition of $N \ll 1$ for waveguide action. These tubes are made of low expansion borosilicate, 7740 Corning glass. Centres of the discharge tubes are placed on 20 mm pitch circle diameter, providing optimum space between adjacent tubes for sealing. Schematic of the laser head is shown in figure 1. The cathode blocks at both ends of the laser head support all the discharge tubes. These blocks of 100 mm$\times$100 mm and 35 mm thickness are made of AISI 304 stainless steel. Discharge tubes pass through two water inlet blocks of dimensions same as of the cathode blocks. These blocks are made of cast Nylon, and mounted near the anodes. Central support blocks of 100 mm$\times$100 mm and 23 mm thickness made of AISI 304 stainless steel are provided between the cathode and water inlet blocks, to avoid sagging of the discharge tubes and to keep them parallel. Both the cathode blocks have a central cavity of 45 mm diameter and 25 mm depth on the side opposite to the discharge tube assembly. The ends of the discharge tubes enter in these cavities through 10 mm long, six holes in the cathode blocks. The annular spaces of these cavities act as common cathode for all discharge tubes. Two tungsten pins of 1 mm diameter are sealed 250 mm apart by glass blowing in the central region of each tube to act as anodes. This optimized inter anode separation is necessary for stable discharge operation. Portions of discharge tubes between the water inlet and cathode blocks on both sides are covered by water jackets made of 45 mm internal diameter Corning glass tubes. All the six supporting blocks of the laser head are mounted parallel on a 1500 mm long MC 150$\times$75 MS channel. Top surface of this channel was finished within 100 microns over its length on a Milling machine.

Chilled water from a water chiller at 18°C and 10 lpm flow rate is used for cooling discharge tubes and cathode blocks. Water enters in cooling jackets through the two water inlet blocks and exits through the channels in cathode blocks. Parts of the discharge tubes between the two Metalon blocks are cooled by forced air. Specially designed silicon rubber gaskets are fitted in the cathode and water inlet blocks for vacuum and water sealing. The gas mixture of CO_2, N_2 and He enters in each discharge tube individually from their central point and flows symmetrically towards the cathode blocks connected to a rotary vacuum pump of 50 lpm pumping speed.

All the six tubes share a common plane parallel resonator. The resonator mirrors are mounted on the outer side of the two cathode blocks. The partial reflecting mirror is a zinc selenide plane mirror of 50 mm diameter and 60% reflectivity. The total reflecting rear mirror is a water-cooled, plane gold-coated copper mirror of 50 mm diameter. These

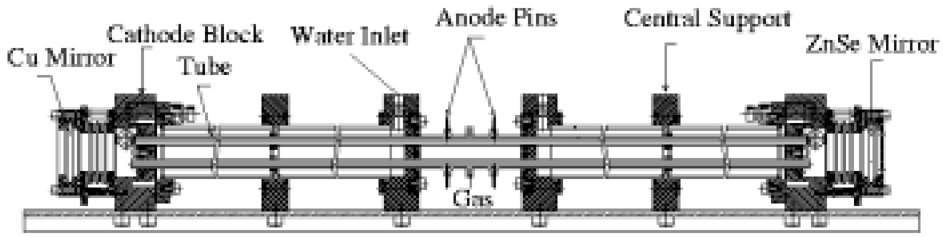

Figure 1. Schematic of the waveguide multibeam CO_2 laser.

mirrors are mounted on the cathode blocks through flexible teflon bellows as shown in figure 1. Both the resonator mirrors are 50 mm away from the waveguide ends forming a symmetric resonator. Smaller mirror distance was not possible due to the mirror mount designed for high alignment stability. Small mirror distance is also not feasible due to the possible damage of mirror coatings by discharge plasma. Two micrometer heads are fitted on each cathode block for aligning the resonator mirrors. Since both the cathode blocks are electrically grounded, the mirrors can be aligned parallel without any electrical hazard.

3. Electrical discharge excitation

Each tube has two discharge sections, electrically in parallel and optically in series, forming one individual resonator. Discharge is to be excited between anode pins and cathode blocks of both sides. This arrangement has the problem of starting DC discharge simultaneously in both sections of every tube without inter anode breakdown. If discharge starts in one side of a tube, invariably it does not extend in other side. To overcome this problem, we have used the technique of pre-ionization in all discharge sections using a HF pulser. The pulser used provides positive pulses of peak 8 kV with repetition rate of 5 kHz and 2μs duration using an SCR as switching device. Such pulses are sufficient to produce the required average electron density for pre-ionization. The pulser is connected to the 12 anode pins in parallel individually through 4700 pF, 15 kV capacitors, isolating the pulser from DC high voltage supply. Pulsed pre-ionization technique for simultaneous excitation of the main DC discharge in all sections of a multibeam CO_2 laser is developed for the first time in our laboratory. We have used this technique for similar purpose in our high power multibeam CO_2 laser with 20 discharge tubes [12] for industrial applications. A compact DC switch mode power supply (SMPS) of 0–14 kV, 250 mAmp rating with negative grounded is designed and fabricated specially for this laser. This SMPS is connected to all the 12 anode pins in parallel through individual ballast of 150 kΩ. Total discharge current flowing through all the discharge sections and DC supply voltage is measured. Pre-ionization allows simultaneous starting of main DC discharge at the high operating pressures without any problem and at voltages less than the breakdown voltage. This reduces the maximum high voltage requirement of the DC supply. Pre-ionization also helps to stabilize the discharge and laser power at lower discharge currents. Thus, the HF pre-ionization technique has solved the problems associated with DC discharge excitation in the waveguide multibeam CO_2 laser.

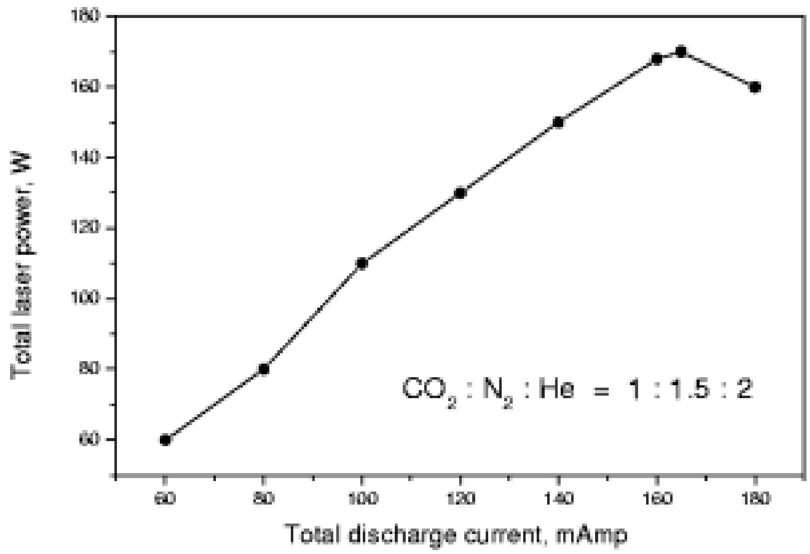

Figure 2. Variation of laser power with total discharge current for optimized gas mixture.

4. Laser performance

After filling the required gas mixture, the HF pulser is put on which produces faint visible discharge, producing sufficient pre-ionization in all discharge sections. The DC high voltage is then applied to get sufficient discharge current in all the tubes giving the required laser power. Laser power was measured for various ratios of gas mixtures and different discharge currents. The gas mixture ratio and discharge current was optimized to get maximum laser power. For measuring the total power of this laser, the six laser beams were broadly focused by a ZnSe meniscus lens of 127 mm focal length and 63 mm diameter on the sensor of Ophir make thermopile-type water-cooled power meter. All these measurements were done with the HF pre-ionizer on. Maximum stable laser power of 170 W has been obtained from this laser with the mixture ratio of $CO_2 : N_2 : He = 1 : 1.5 : 2$ with total pressure of 49 mbar and total discharge current of 165 mAmp. Maximum power is obtained with electro-optical efficiency of 10%. Variation of total laser power with discharge current for the mixture giving maximum power is shown in figure 2. Transverse modes of all the laser beams were checked by observing burn patterns on a thick Perspex block. At different output powers, all the beams showed conical intensity distribution as shown in [6], confirming that the laser operated in EH_{11} waveguide mode. Diameter of all the beams was 5 mm as expected with a plane parallel resonator.

Considering the EH_{11} mode of all the beams, suitability of this laser for cutting wood was checked. An available motorized linear motion controller of variable speeds was used to mount the wooden piece so that the stationary laser beams could be focused on it. A conical nozzle of aluminium was fabricated to accommodate the ZnSe lens used for power measurements. This nozzle has copper exit tip of 2 mm diameter and gas inlet connection. The nozzle was mounted horizontally in front of the output mirror of this laser. Commercial argon gas was used as shroud gas for woodcutting. Plywood of different thickness up to 6 mm was cut using this set-up. The 6 mm thick plywood could be cut with good cut quality at a speed of 100 mm/min with inlet pressure of 2 kg/cm^2 of argon gas. Focusing of all the beams of a multibeam laser in the exit tip is difficult compared to a single beam laser. Better alignment of the gas nozzle can improve the cutting speed and cut quality. This experiment has demonstrated that this laser can be used for woodcutting in various shapes using computerized motion controller.

5. Discussions

Considering the maximum power of 170 W presently obtained from six tubes of 1 m-cooled discharge length, the specific power is 28 W/m. This specific power can be compared with those obtained from the AC excited waveguide multibeam CO_2 lasers having discharge tubes of almost similar diameter and output mirror reflectivity. The lasers mentioned in [10] and [11] have specific powers of 17 W/m and 14 W/m with the electro-optical and overall efficiencies of 13% and 6% respectively, as reported. These specific powers are much lower compared to that obtained from the present laser. This may be due to the use of copper rear mirror of lower reflectivity and inefficient heat removal due to oil cooling. In these lasers, the gas mixture enters from one end of the discharge tube and exits from the other end. Dissociation of CO_2 is highest in the region where the fresh active mixture enters in discharge zone and continues with distance in the discharge [13]. Longer path of gas mixture in discharge zone thus increases its degradation and may be resulting in lower specific power from those lasers. In the present laser, central injection of the gas mixture in each tube reduces the mixture path or its residence time in discharge zone.

All discharge tubes of this laser are identical and independent resonators, exhibiting the same transverse waveguide mode. It is necessary to check the modes, which can be supported by this laser using the theoretical analysis for circular waveguide with flat mirrors. For a symmetric circular resonator with plane mirrors at distance d and $k = 2\pi/\lambda$, Gerlach *et al* [8] have shown that when d/ka^2 is around 0.02 or smaller, EH_{11} mode has the lowest loss. For $d/ka^2 < 0.02$, mixing of EH_{11} and EH_{12} modes is possible near the points of degeneracy when l/ka^2 is between 0.45 and 0.50. For the present laser, $d/ka^2 = 0.01349$ and $l/ka^2 = 0.3900$. These values show that only the EH_{11} mode will be the predominant mode of all the beams of this laser and they are away from the points of degeneracy. Hill and Hall [14] have shown that for circular guides with flat mirrors, when $z/z_0 < 0.1$, the percentage coupling loss of EH_{11} mode nearest to the experimental values is given by

$$\Gamma = 158\{z/z_0\}^2,$$

where $z = d$ and $z_0 = \pi w_0^2/\lambda$. For the present laser, $z/z_0 = 0.06518$ and using the above expression, the coupling loss for EH_{11} mode is 0.671%. These discussions confirm that the present laser can operate only in EH_{11} waveguide mode.

6. Conclusions

A waveguide multibeam CO_2 laser of 170 W output power is made operational using DC excitation with the high frequency discharge pre-ionization technique. All beams are operating in waveguide EH_{11} mode. The specific power of 28 W/m is much higher compared to that obtained from AC-excited waveguide CO_2 lasers. The pre-ionization technique allows simultaneous excitation of DC discharge in all discharge sections at voltages much lower than the breakdown voltage. The DC excitation allows using water-cooling which is more efficient than the oil cooling. Theoretical analysis of the resonators shows that only EH_{11} mode will be predominant for all beams of this laser. Such a laser designed for higher output power can be used for cutting non-metals.

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