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Indigenous development of a 2 kW RF-excited fast axial flow CO_2 laser

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Abstract. RF-excited fast axial flow CO_2 lasers in kilowatt regime are presently being used for various new scientific applications in addition to laser material processing because of its versatility and superior beam quality. We have indigenously developed a compact 2 kW RF-excited fast axial flow CO_2 laser with moderate beam quality. In this paper the key design features of the laser and the associated high power capacitively coupled RF excitation technique are discussed in detail. Operational characteristics of this system are described along with the experimental findings.

Keywords. CO_2 laser; RF excitation; fast axial flow; impedance matching; laser material processing.

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1. Introduction

High-power RF-excited fast axial flow (RF-FAF) CO_2 laser is becoming one of the attractive tools for advanced research in the areas of generation of monoenergetic MeV photons, particle acceleration, development of EUV source at 13.5 nm for high volume chip manufacturing and nanoparticles synthesis apart from various industrial material processing applications [1–5]. These lasers have found applications in the industry and research community due to its high wall-plug efficiency, compactness, clean RF discharge technology, good beam quality ($M^2 \sim 1.6$) even at high power, high modulation frequency up to 100 kHz and scalability to higher powers without sacrificing the beam quality [6,7]. In some laser material processing applications, e.g., thick metal cutting, keyhole welding, drilling, forming, rapid prototyping and surface hardening, these lasers are still preferred to Nd:YAG, fibre and diode lasers mainly due to its superior beam quality at multi-kilowatt level.

To achieve CW output power in kilowatt regime, the gaseous active medium of the CO_2 laser needs to be circulated at a high velocity either transversely or axially to the optical axis and passed through the heat exchangers, which remove the discharge heat. Since the last decade, multi-kilowatt transverse flow transverse discharge (TFTD) CW CO_2 lasers were being widely used in laser material processing applications. But, these lasers are not only very bulky but also suffer from poor beam quality mainly because of the larger physical width of the gain medium, which supports a multitude of transverse modes. This significantly reduces the laser power density at the focus and limits the range of its applicability. On the contrary, FAF CO_2 laser can be made fairly compact and usually ensures high beam quality owing to the cylindrical confinement of RF-discharge in narrow tubes which allows only a few lower-order transverse modes to oscillate in the resonator. The RF excitation has the merits of providing extended area uniform discharge, higher power density and high modulation frequency in comparison to the DC-excited FAF CW CO_2 laser. All these advantages combined together make the RF-FAF CO_2 laser the state-of-the-art technology for many challenging applications. Recently, we have developed a 2 kW RF-FAF CO_2 laser with moderate beam quality and good power stability. In this paper we discuss the design and development of high-power RF-FAF CO_2 laser, which was taken up at our Division, looking at its potential applications in diverse scientific and technological areas of crucial importance.

2. Design aspects of the laser system

Laser head: The high-power RF-excited FAF CO_2 laser system developed by us uses a high-speed (rotating at 44,000 rpm) turboradial blower (Leybold make, model: TST 1500 S) for flowing the laser gas through parallel discharge tubes. The turboblower is capable of delivering a volumetric flow rate of 1500 m^3/h and can produce a maximum compression ratio of 1 : 1.4 at an operating pressure of 115 mbar of CO_2 laser gas mixture comprising of CO_2, N_2 and He. The gas flow

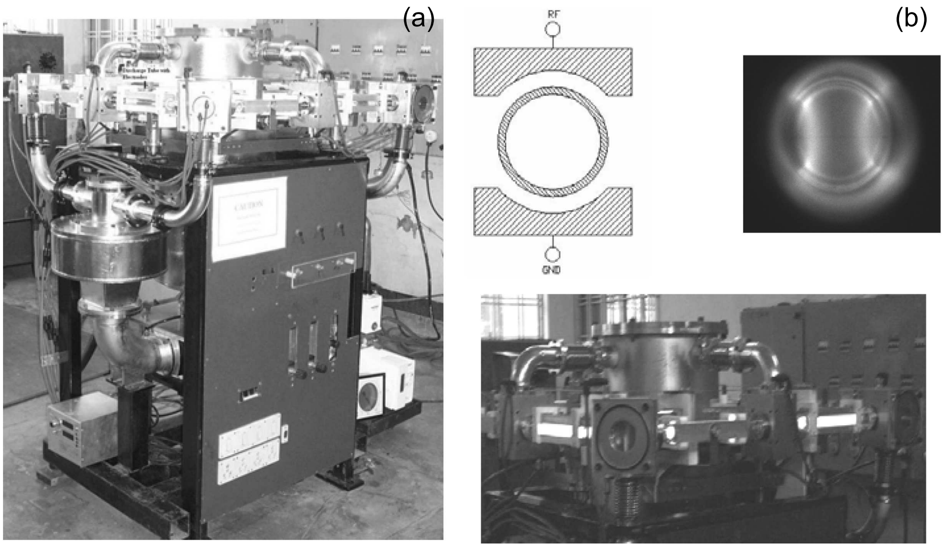

Figure 1. (**a**) RF-FAF CW CO_2 Laser. (**b**) Electrodes assembly, end-on view of RF glow discharge, simultaneous RF-excitation.

from the blower is divided into eight parallel discharge tubes, which are mounted around a square frame. The blower is placed just beneath the square frame such that its axis of rotation passes through the centre of the frame. This unique geometry not only makes the RF-FAF laser system compact (footprint: 1 m $\times$ 1 m) but also ensures symmetrical gas flow and uniform RF power feeding in all the tubes. Figure 1a depicts the RF-FAF CO_2 laser head. The compressed laser gas mixture comes out of the two outlet ports of the blower and passes through two heat exchangers, which remove the heat due to compression. The gas flow is then bifurcated in two parts, each part being guided to one of the four corner blocks mounted on the square frame. Each corner block finally guides the flow through two quartz discharge tubes having 20 mm i.d. connected at 90° to it. The axial gas flow velocity through the tubes is about 160 m/s, which is sufficient to restrict the rise in gas temperature in the discharge tubes below 250°C required for smooth operation of the laser. After flowing through the discharge zone, the separated gas flows are recombined at the four water-cooled mixing blocks connected at the centre of each arm of the square frame before finally passing through the main heat exchanger to the blower inlet. The pressure drops occurring at the various components of the gas flow loop could be overcome by the head generated by the blower. RF power is fed to the spherically profiled aluminium electrodes fitted externally to the discharge tubes and gets capacitively coupled to the laser gas mixture through the intervening air gap and the dielectric (figure 1b). The length of the electrode is decided by the axial gas flow velocity v_{f}, input power density p_{in}, the optimum rise in gas temperature $\Delta T_{\mathrm{opt}} = 250°\mathrm{C}$ and the electro-optic efficiency η and turns out to be 21 cm for each tube. According to an empirical power scaling law, the output power of a convectively cooled CO_2 laser scales up with the mass flow rate $\dot{m}$ [8]. With the total mass flow rate $\dot{m} \sim 20$ g/s at 110 mbar operating pressure this laser system is expected to generate an output power in excess of 2 kW. The optical resonator of this laser has also been formed around the square frame having three flat folding mirrors in addition to the concave rear reflector of 15 m ROC and the flat ZnSe output coupler with 50% feedback. All the total reflectors and the output coupler have been mounted on the four corner blocks and are water-cooled. The resonator is designed to have a low Fresnel number ($N \approx 2.5$) to allow the oscillation of only one or two lower-order transverse modes, thereby ensuring a good beam quality.

High-power capacitively-coupled RF discharge excitation: The requirement of RF input power was estimated from the desired output laser power and the nominally expected electro-optic efficiency of 15%. The choice of operating frequency for discharge excitation in the glow regime by the RF power is decided by the mode of RF coupling, sheath thickness, gas pressure, discharge tube diameter, type of plasma, average electron density and thermal instability allowance [9,10]. Based on the above criteria, the RF generator requirement was evolved into 15 kW RF power at 13.56 MHz, which was to be deposited in the laser discharge load matched to the 50Ω coaxial cable. Accordingly, a 20 kW RF power oscillator was successfully developed around an E2V triode BW1606J2F based on Hartley configuration operating in self-biased Class C mode with an efficiency of 60% at the maximum power level. Figure 2 shows the circuit diagram of the RF power source. The Q of the

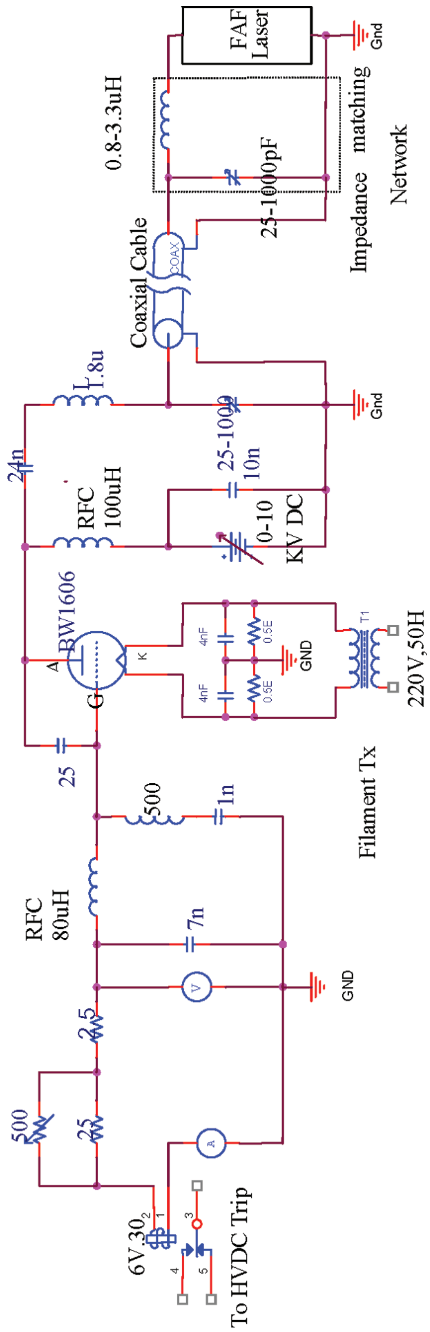

Figure 2. Circuit diagram of RF excitation source with impedance-matching network.

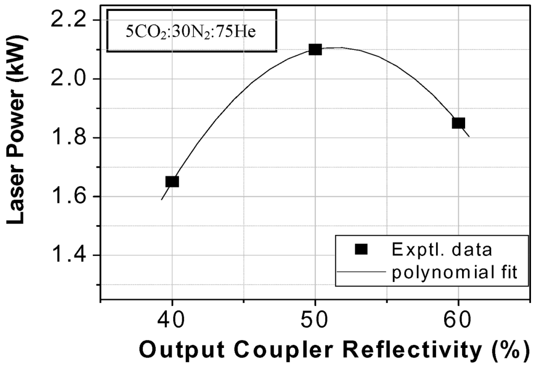

Figure 3. Optimum coupler reflectivity.

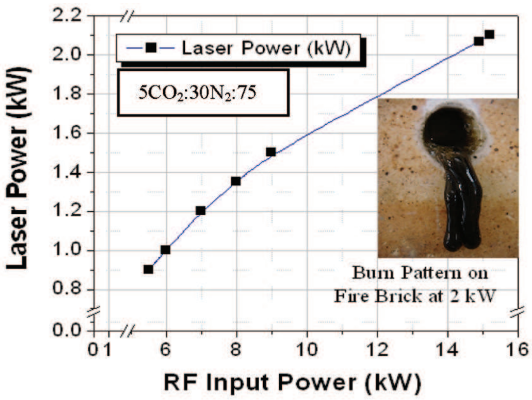

Figure 4. Laser power vs. RF input power (inset) Burn pattern at 2 kW.

tank circuit is between 6 and 7. The RF power from this oscillator is coupled through a 50Ω flexible Times Microwave make LMR 1200DB coaxial cable to the RF-FAF CO_2 laser head. The electrical equivalent of capacitively coupled RF discharge for CO_2 laser excitation is modelled as a series combination of resistance and capacitance for a single discharge tube. As mentioned in laser head geometry, eight quartz tubes are used for discharge excitation. They are simultaneously fed with RF power by symmetric and parallel connections using 30 mm wide and 1.5 mm thick copper strips. The equivalent laser impedance for such a geometry is again a series combination of resistance and capacitance but with modified values. The effect of capacitance due to the laser structure is also accounted for. This impedance needs to be transformed into 50Ω for maximizing the power feed. This transformation is realized by inserting an L-type impedance-matching network between the laser head and the RF cable [11]. The working values of this L-type network were found to be L: 0.8 μH and C: 400 pF for about 14 kW RF input deposition into laser load with VSWR at the oscillator ∼1.1.

3. Operational characteristics and experimental results

Upon ensuring the prerequisites of vacuum integrity, gas mixture, operating pressure, axial gas flow and its temperature rise, the laser system was energized with the RF power. By increasing plate voltage and tuning the variable capacitor in the oscillator, the RF power is fed simultaneously into the discharge tubes (figure 1b). At nearly 2 kV peak RF voltage across each tube, the gas is ignited and glow discharge is visible. The variable capacitor in the matching network was tuned to minimize the reflected power and the forward power was increased till the required RF input power density is achieved. At about 14 kW RF input power uniform discharge fills almost 80% of the tube cross-section indicating a maximum input power density of about 33 W/cc. Under matched condition at 14 kW, the minimum reflected power of 50 W was achieved at the RF oscillator. The resonator optics were mounted and accurately aligned to extract the maximum power from the laser head. Experiments were performed to choose the optimum reflectivity of the output coupler and maximize the laser power for a given gas mixture. The ratio of the constituent gases was changed to approach the optimal mixture. It was found that maximum power could be obtained with an optimum output coupler reflectivity of 50% (figure 3), gas mixture ratio of $CO_2 : N_2 : He::1 : 6 : 15$ at 110 mbar total pressure and at an input power of 14–15 kW. At these operating conditions, a maximum of 2.1 kW power was achieved with 14% efficiency. The RF input power vs. laser output power for the optimal gas mixture is shown in figure 4. The output laser beam comprised of only two lower-order transverse modes with an estimated beam propagation factor $M^2 \sim 3$. The burn pattern of the laser beam on a firebrick is shown in figure 4 (inset). The short-term (in continuous operation over 1 h) output power stability of this laser was measured and is $\sim\pm 1.5\%$ at 1 kW level. Experiments were performed to study the control of RF power by switching the grid bias voltage or the anode voltage and varying the duty cycle from 10 to 80% at any frequency from 100 Hz to 20 kHz [12]. Later the second scheme was used to control the laser power from 10 to 100% at any frequency from 100 Hz to 10 kHz.

4. Conclusions

A high-power RF-excited FAF CW CO_2 laser was designed, indigenously developed and successfully operated at 2.1 kW level with most of the design objectives being met. Compactness, good beam quality and high output power stability are the noteworthy features of this laser.

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