Continuous wave operation of a non-self-sustained electric discharge pumped oxygen-iodine laser


Department of Mechanical Engineering, The Ohio State University, Columbus, Ohio 43210

(Received 26 October 2006; accepted 15 November 2006; published online 15 December 2006)

This letter discusses operation of an electric discharge excited oxygen-iodine laser using a high-pressure, non-self-sustained pulser-sustainer discharge. Small signal gain on the 1315 nm iodine atom transition and the laser output power are measured in the M=3 supersonic cavity downstream of the discharge section. In a 15% O₂–85% He mixture, at a discharge pressure of 60 torr and discharge power of 1.5 kW, the highest gain measured in the M=3 cavity is 0.022%/cm, at the flow temperature of T=100±10 K. At these conditions, the laser output power is 0.28 W. © 2006 American Institute of Physics. [DOI: 10.1063/1.2408668]

Development of an electric discharge pumped chemical oxygen-iodine laser (or discharge excited oxygen-iodine laser) recently attracted considerable attention, especially after measuring positive gain in the supersonic laser cavity and the successful laser power generation. One of the main objectives of this on-going effort is scaling the laser output power. This can be done by (i) increasing the electric discharge pressure, without producing ionization instabilities and arc filament formation, (ii) increasing singlet delta oxygen (SDO) yield in the discharge while reducing oxygen dissociation in the plasma, and (iii) lowering the plasma temperature before it enters the laser cavity using a rapid supersonic expansion. Recent experiments in a rf discharge in O₂–He mixtures at P=10 torr followed by a M=2 expansion demonstrated positive gain on a 1315 nm iodine atom transition and cw lasing with a 220 mW output power at the cavity temperature of T=190 K. Using a higher cavity Mach number would allow further lowering the flow temperature during the expansion, while operating at a higher discharge pressure (for the same cavity pressure). For a M=3 cavity pressure of P=2–4 torr, the stagnation pressure in a 10% O₂–He flow should be P₀=65–130 torr. Also, to optimize SDO yield in the plasma, the high-pressure discharge should operate at reduced electric field (E/N) values where the energy input into the O₂(a 1Δ) state is maximum, E/N < 10 Td (townsend), which suggests the use of a non-self-sustained electric discharge, with an external ionization source uncoupled from the applied electric field. An additional advantage of such discharges is that they remain stable at high pressures and energy inputs.

The approach used in the present work employs two overlapping discharges in a rectangular geometry, a repetitively pulsed discharge and a dc sustainer discharge. In this approach, uniform ionization is produced by high voltage, high repetition rate ionizing pulses, with the pulse duration too short to allow ionization instability development. The pulse repetition rate is sufficiently high to avoid complete plasma decay between the pulses. The dc voltage is too low to produce additional ionization, so that the decaying plasma remains stable. The dc voltage, which can be tailored to maximize the energy input into the O₂(a 1Δ) state, couples power to the plasma. This method, demonstrated by Hill, has been previously used to develop a high-power, fast flow CO₂ laser. Our previous work showed that this approach produced stable and diffuse plasmas in O₂–He flows, at high pressures and discharge powers, up to at least P₀ =120 torr and 2.2 kW, and in the E/N range of at E/N =3–12 Td, which incorporates the optimum value for O₂(a 1Δ) excitation. SDO yield measured at these conditions was up to 5.0%–5.7%.

A schematic of the experiment is shown in Fig. 1. A premixed O₂/He mixture is flowing through a 5×2 cm² rectangular cross section, 12 cm long discharge section, made of acrylic plastic. Two copper dc electrodes, 5 cm², and two copper pulsed electrodes, 5×5 cm², are flush mounted in the sidewalls and in the top/bottom walls of the discharge section, respectively. The pulsed electrodes, insulated from the flow by alumina ceramic plates 1 mm thick each, are powered by a high voltage (20 kV), short pulse duration (~10 ns), high pulse repetition rate (up to 100 kHz) FID Technology plasma generator. The dc electrodes are powered by a Glassman dc power supply (5 kV, 2 A), operated in the voltage-stabilized mode. A high-power ballast resistor (R=1 kΩ) is connected in series with the dc electrodes. The dc sustainer current is measured by a Tektronix A6303/AM503B current probe/amplifier. Two BK-7 glass windows are located 5 cm downstream of the discharge section (see Fig. 1) for singlet delta oxygen yield and rotational

---

**FIG. 1.** Schematic of experimental setup.

---

*Electronic mail: adamovich.1@osu.edu*
The discharge section is followed by a $M=3$ nozzle and a supersonic cavity (see Fig. 1). The nozzle throat and exit dimensions are $5 \times 0.32$ cm$^2$ and $5 \times 1$ cm$^2$, respectively. The discharge section/nozzle throat area ratio, $A/A^* = 6.25$, corresponds to a Mach number of $M \approx 0.1$, so that the discharge section serves as the nozzle plenum. The discharge pressure (i.e., stagnation pressure) and the mixture composition can be varied independently. At $P_0 = 120$ torr, 10% O$_2$ in He, the flow rates are 32 mmole/s of O$_2$ and 290 mmole/s of He. The top and bottom walls of the supersonic section are diverging at 1.5$^\circ$ each to provide boundary layer relief. Multiple static pressure taps are located in the bottom wall of the cavity for supersonic flow characterization. Between the runs, the 1000 ft$^3$ vacuum tank is pumped down to $\sim 0.1$ torr using a Stokes 212-H 150 ft$^3$/min vacuum pump.

Two stainless steel arms, 1 in. in diameter and 6 in. in length each, are attached to the cavity sidewalls at the downstream end of the cavity for small signal gain measurements and laser power measurements. For the gain measurements, stainless steel flanges with 10 mm diameter, wedged, and antireflection coated BK-7 glass windows are attached to the end of the arms. For the laser power measurements, the gain window flanges are replaced with two adjustable vacuum mirror mounts, attached to the end of the arms to form a stable resonator. In the present measurements, we used two Los Gatos Research mirrors with the 99.99% reflectivity at 1315 nm and the radius of curvature of 1 m. Both the gain windows and the laser mirrors are separated by approximately 40 cm. This modular arrangement allowed gain and laser power measurements at the same location and at the same flow conditions. To protect gain windows and laser mirrors from iodine deposits, two auxiliary helium curtain flows are injected into the supersonic cavity on both sides of the main $M=3$ flow using two $M=3.5$ nozzles. In addition, the resonator arms can be independently purged by separate helium flows.

Iodine vapor is added to the main flow using an iodine metering/delivery system developed at Physical Sciences Inc. (PSI). Iodine vapor is produced by passing helium carrier gas over heated iodine crystals. I$_2$ concentration in the flow is measured by molecular iodine continuum absorption at 488 nm. The iodine-helium mixture is injected into the flow through two stainless steel injection blocks upstream of the nozzle throat (see Fig. 1). In the present experiments, iodine crystals were heated up to 40 $^\circ$C, producing I$_2$ vapor flow rate of up to 60 $\mu$ mole/s, at the He carrier flow rate of up to 60 mmole/s.

All flows through the test section (main oxygen/helium mixture, curtain helium, iodine vapor/helium mixture, and purge helium) are started simultaneously using remotely controlled solenoid valves. Static pressure measurements in the laser cavity (without the resonator arms), at plenum pressures of $P_0 = 60$ and 111 torr in 10% O$_2$–He flows, show that steady-state supersonic flow is sustained from 20 s ($M = 2.9$, nozzle exit) to 5 s ($M = 3.1$, downstream end of cavity). The pressure slightly decreases and the Mach number increases in the direction of the flow because of the divergence of the cavity walls (see Fig. 1). With the resonator arms in place near the downstream end of the cavity, the static pressure in the resonator is steadily rising during the run, from $P$ = 2.0 to 2.5 torr over 5 s, indicating the Mach number reduction from $M = 3.0$ to $M = 2.7$. In the present measurements, no supersonic diffuser has been used. After the flows are started, the pulsed discharge and the sustainer discharge are turned on. In the present measurements, the high voltage pulse repetition rate was varied from $v = 10$ to 100 kHz, and the dc power supply voltage was varied from $U_{PS} = 1.5$ to 2.5 kV, at the ballast resistor of $R = 1$ k$\Omega$. At $P_0 = 60$ torr, the time-averaged sustainer discharge power was 1.5 kW and the estimated reduced electric field was $E/N = 8$ Td. At these conditions, the crossed discharge remained non-self-sustained (turning the pulser off terminated the discharge).

A small signal gain at 1315 nm in the $M=3$ cavity is measured by tunable diode laser absorption spectroscopy using the PSI iodine scan sensor. In the absence of excited iodine atoms, the sensor measures absorption by the ground state I atoms. When excited iodine atoms, I*, are generated by energy transfer from SDO, the sensor measures a combination of absorption and stimulated emission. Positive gain across the optical path of $L = 5$ cm is measured when population inversion is achieved in the flow ($|I^*|/|I| > 1/2$). The recorded spectra, each averaged over a 0.5 s period, are used to calculate optical gain/loss at the line center and the flow temperature from the line shape profile. The laser output power is detected using a New Focus model 5842 infrared card and measured by a Scientech power meter.

Figure 2 shows time dependent absorption/gain signal measured during a single run in a 15% O$_2$–He flow, at $v = 34$ kHz, $U_{PS} = 2.5$ kV, $I = 1.2$ A, and I$_2$ flow rate of 50 mmole/s. Without plasma, no iodine atoms are generated in the flow, so that the optical path is transparent. When the pulser alone is operating, O atoms are produced by electron impact dissociation of O$_2$ during high voltage pulses, while no significant singlet delta oxygen is produced. O atoms generate I atoms in the flow by rapid chemical reactions with the iodine vapor. At these conditions, absorption was observed on the I($^3P_{3/2}$)–I($^3P_{1/2}$) transition (see Fig. 2). When both the pulsed discharge and the dc discharge are operating, both O$_2$(a $^1$Δ) and O atoms are generated in the discharge section. In this case, excited iodine atoms are produced in the flow by energy transfer from O$_2$(a $^1$Δ) to ground state iodine atoms. This produces population inversion and results in an optical absorption signal.
gain of up to 0.022%/cm, as shown in Fig. 2. Turning the dc discharge off, with the pulser still operating, removes SDO molecules while O atoms are still present in the flow, which reverses gain to absorption. Finally, turning the pulsed discharge off removes the O atom source and returns the optical path to transparency. Figure 3 shows a typical Doppler fit to the experimental gain line shape, yielding a translational temperature in the cavity of $T = 100 \pm 10$ K. The temperature, inferred from both absorption and gain line shapes, remains nearly constant (within the uncertainty of $\pm 10$ K) during the entire run. This is in very good agreement with the rotational temperature measured by emission spectroscopy, $T = 120 \pm 15$ K. However, the gain decreases during the run by approximately 20% over 3 s (see Fig. 2).

At these conditions, a single-pass gain, about 0.11%, would exceed the laser mirror loss, about 0.01%, by an order of magnitude. Also, the measured gain is more than a factor of 3 higher than measured in Ref. 7, at the conditions when lasing was detected. This suggested that lasing could also be achieved at the present experimental conditions. Indeed, replacing the gain windows with the laser mirrors demonstrated cw lasing, detected using both the infrared card and the power meter. Figure 4 shows the laser output power measured by the power meter. Since the response time of the power meter ranges from 5 to 10 s, the signal increases with time due to a long response time of the power meter (5–10 s).

This work was supported by the Joint Technology Office. The authors would like to express their gratitude to T. Madden, G. Hager, and D. Hostutler of AFRL, as well as W. Solomon and D. Carroll of CU Aerospace.