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Gain and continuous-wave laser power enhancement with a multiple discharge electric oxygen-iodine laser

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Herein the authors report on the demonstration of a 70% enhancement in gain and 98% enhancement in continuous-wave laser power on the 1315 nm transition of atomic iodine via an increase in flow rates and pressure using multiple discharges in an electric oxygen-iodine laser. $O_2(a\ ^1\Delta)$ is produced by two parallel radio-frequency-excited electric discharges sustained in an O_2–He–NO gas mixture, a secondary discharge predissociated the molecular iodine, and $I(^2P_{1/2})$ is then pumped using energy transferred from $O_2(a\ ^1\Delta)$. A gain of 0.17% cm^{-1} was obtained and the total laser output power was 12.3 W. © *2008 American Institute of Physics*.
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The electrically driven oxygen-iodine laser (ElectricOIL) that was first demonstrated by Carroll *et al.*[1,2] operates on the electronic transition of the iodine atom at 1315 nm, $I(^2P_{1/2}) \rightarrow I(^2P_{3/2})$ (denoted hereafter as I^* and I, respectively). The lasing state I^* is produced by near resonant energy transfer with the singlet oxygen metastable $O_2(a\ ^1\Delta)$ [denoted hereafter as $O_2(^1\Delta)$]. Subsequent efforts have demonstrated gain[3–5] and lasing[4,5] in other ElectricOIL configurations since the first demonstrations. Ionin *et al.*[6] provided a comprehensive topical review of discharge production of $O_2(^1\Delta)$ and ElectricOIL studies by various groups. In these prior ElectricOIL experiments, investigators relied upon O atoms to provide the predominant mechanism for iodine dissociation. However, with the desire to push the system to higher flow pressures, there are fewer O atoms available due to recombination. Thus, to achieve more complete dissociation in ElectricOIL, the use of an iodine predissociator is of particular importance at higher flow pressures. Carroll and Solomon[7] first hypothesized and calculated, and Benavides *et al.*[8] recently demonstrated experimentally that this technology improvement was very important for the ElectricOIL system to maximize the energy transfer of $O_2(^1\Delta)$ into atomic iodine, and consequently significantly enhance gain and laser power output.

In this letter, the authors report on the demonstration of a 70% enhancement in gain and a 98% enhancement in continuous-wave laser power on the 1315 nm transition of atomic iodine through the use of two parallel primary discharges at higher total flow rates and pressure plus a secondary discharge to predissociate the molecular iodine (the same used in Ref. 8) in an electric oxygen-iodine laser. The $O_2(^1\Delta)$ is produced by two parallel capacitive 13.56 MHz electric discharges sustained in an O_2–He–NO gas mixture, and I^* is then pumped using energy transferred from $O_2(^1\Delta)$; the electrode gaps in the primary discharges are transverse to the flow direction, and the discharges are matched in parallel from a single power supply. A block diagram of the flow tube setup is shown in Fig. 1. Both of the plasma zones filled the transverse gap and were approximately 1.6 cm in diameter and 25 cm long (the outside diameter of each of these discharge tubes was 1.9 cm). In prior experiments, a single 4.9 cm diameter plasma zone was utilized (discharge tube with outside diameter of 5.1 cm). The change to smaller diameter discharge tubes was motivated by a detailed series of work summarized by Braginsky *et al.*[9] in which they demonstrated that smaller diameter tubes had substantially increased discharge stability at higher pressure while maintaining significant $O_2(^1\Delta)$ yields. More information on the performance of the transverse electric discharge sustained in an O_2–He–NO gas mixture used in the experiments presented herein can be found in Ref. 10. A secondary rf discharge[8] was placed at the exit of the iodine injection holes using electrodes embedded in injector blocks fabricated out of the machinable ceramic Macor®.

The supersonic diagnostic cavity has a Mach 2 nozzle with purged optical mounts into which can be placed either wedged windows for measurement of the gain or high-reflectivity mirrors for laser oscillation. The gain length of the laser cavity is 5 cm. Simultaneous measurements of the optical emission from $O_2(^1\Delta)$ at 1268 nm and $O_2(b\ ^1\Sigma)$ at 762 nm are made 7.5 cm downstream from the exit of the two discharges through the wall of a Pyrex flow tube in the subsonic observation region. A Roper Scientific optical multichannel analyzer (OMA-V) with a 1024-element InGaAs LN_2 cooled array interfaced to an Acton Research SP-2300i monochromator was used for measurements at 1268 nm. A thermoelectric-cooled Apogee charge-coupled device is used to measure spectra of the $O_2(b\ ^1\Sigma)$ transition about 762 nm.

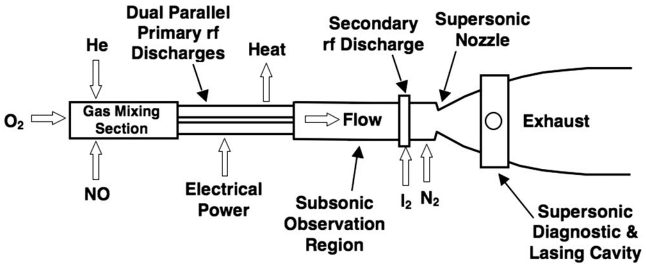

FIG. 1. Schematic of the experimental apparatus.

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Both instruments are fibercoupled to enable instrument positioning flexibility and excellent measurement repeatability.

Micro-Motion CMF and Omega FMA mass flow meters were used to measure the flow rates of the gases. The I_2 concentration was measured by a method developed by Physical Sciences Inc. (PSI) and is based on the continuum absorption of molecular iodine at 488 nm. Details of this diagnostic are described by Rawlins *et al.*[11] Pressure in the subsonic and supersonic flow regions were measured by capacitance manometers from MKS and Leybold.

Measurements of gain (or absorption) were made prior to running the apparatus as a laser using the iodine-scan diagnostic (ISD) developed by PSI.[12] The ISD is a diode laser based monitor for the small signal gain in iodine lasers. The system uses a single mode, tunable diode laser that is capable of accessing all six hyperfine components of the atomic iodine. It was calibrated in frequency to enable automated operation for the (3,4) hyperfine transition for our experiments. A fiber optic cable was used to deliver the diode laser probe beam to the iodine diagnostic regions in the subsonic portion of the flow tube and in the supersonic cavity. Since the ISD uses a narrowband diode laser, measurements of the lineshapes can also be used to determine the local temperature from the Voigt profile.

The windows on the sides of the cavity when using the gain diagnostic were wedged and antireflection coated to minimize etalon effects. A single pass configuration (5 cm path length) was used in the supersonic diagnostic section. Measurements of the $O_2(^1\Delta)$ yield $\{$defined as $Y = O_2(^1\Delta)/[O_2(^3\Sigma)+O_2(^1\Delta)]\}$ were obtained from OMA-V calibrations involving gain measurements and the relative values of the spectral intensities measured for I^* to $O_2(^1\Delta)$ using techniques originally developed by Hager[13] and Davis *et al.*[12]

Laser power measurements were made with a Scientech Astral™ model AC5000 calorimeter interfaced to a Scientech Vector™ model S310 readout, and were made at the same location in the supersonic laser cavity as were the gain measurements. The gain measurements were made first. The mirrors were then put in place for the laser power trials. Two 99.990% reflective mirrors purchased from Los Gatos Research, each with 2 m radius of curvature, formed a stable optical cavity. The mirrors were separated by approximately 34 cm. An infrared detection card from New Focus, model 5842, with response between 800 and 1600 nm, was also used to observe the intensity profile of the beam.

The flow conditions for these gain and laser power experiments with the dual primary discharges and the I_2 predissociator are 20.0 mmol/s of O_2 which is diluted with 66.0 mmol/s of He and 0.08 mmol/s of NO. The discharge production of $O_2(^1\Delta)$ was enhanced by the addition of a small proportion of NO to lower the ionization threshold of the gas mixture and improve discharge stability. The NO also significantly reduces the concentration of atomic oxygen, which has been shown to quench the desired I^* state.[14,15] A secondary stream of ≈0.065 mmol/s of I_2 with 18.0 mmol/s of secondary He diluent was injected 27.3 cm downstream from the exit of the primary discharge and run through a 100 W rf secondary discharge. A tertiary flow of 215 mmol/s of cold N_2 gas (≈100 K) was injected further downstream to lower the temperature and to raise the pressure to improve the performance of the nozzle in our vacuum system. The pressures in the subsonic diagnostic duct and in the supersonic diagnostic cavity were 43.0 and 4.6 Torr, respectively. Measurements in the subsonic diagnostic duct from the $O_2(^1\Delta)$ and $O_2(b\ ^1\Sigma)$ spectra indicated an $O_2(^1\Delta)$ yield of ≈11% and a gas temperature of ≈415 K for these flow conditions at 1000 W of rf power in each of the two primary discharges (a total of 2000 W).

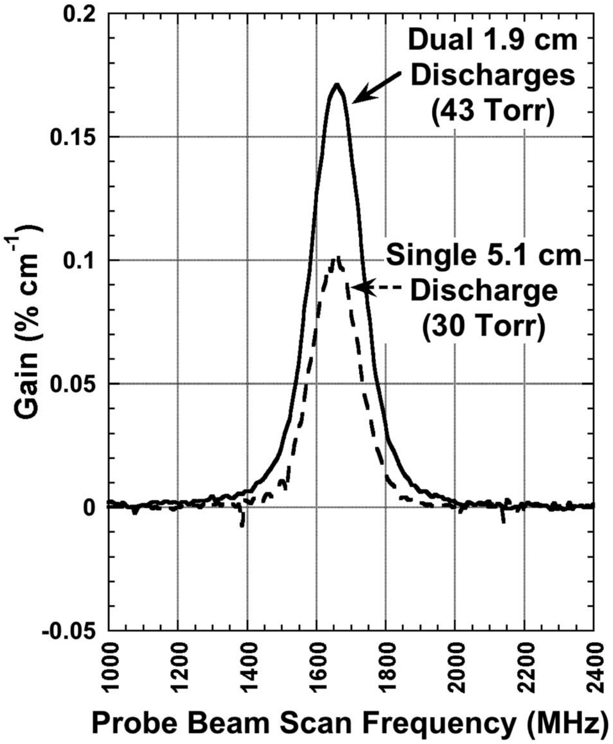

FIG. 2. Gain lineshapes in the supersonic cavity as a function of probe beam scan frequency with dual parallel 1.9 cm diameter discharges operating at 43 Torr (4.6 Torr in supersonic cavity) and with a single 5.1 cm diameter discharge operating at 30 Torr (3.2 Torr in supersonic cavity).

Gain was measured for the above flow conditions at a total of 2000 W of primary rf discharge power and 100 W of secondary rf discharge power for the I_2 predissociator. Figure 2 shows the gain at the line center which peaks at 0.17% cm^{-1} with the dual 1.9 cm diameter primary discharges and the I_2 predissociator secondary discharge. For comparison, the best gain previously observed[8] in our system of 0.10% cm^{-1}, using a single 5.1 cm diameter primary discharge and a little more than half of the flow rates at 30 Torr total pressure (3.2 Torr in the supersonic diagnostic cavity), is also shown in Fig. 2; the dual discharge provides a 70% $[=(0.17-0.10)/0.10]$ enhancement in gain as compared to the previous best results. The lineshape indicates a temperature of ≈125 K. Note that turning off the I_2 predissociator secondary discharge resulted in a 30%–40% (depending on flow conditions) drop in the magnitude of the gain; therefore, this secondary discharge continues to prove to be an important technology enhancement.

The laser resonator was subsequently installed around the 5 cm gain length supersonic cavity. For the above 43 Torr flow conditions, a total laser output power of 12.3 W was obtained, a 98% improvement to laser power relative to the 6.2 W result from Ref. 8. The beam shape was rectangular with rounded corners and had a length of ≈3.5 cm in the flow direction and a height of ≈1.8 cm (the same dimensions as the clear aperture of the mirror mounts in the flow direction and the height of the nozzle at the center of the beam in the vertical direction).

In conclusion, the authors observed a 70% enhancement in gain and 98% enhancement in continuous-wave laser power on the 1315 nm transition of atomic iodine through the use of dual 1.9 cm diameter primary discharges operating at higher flow rates and pressures, in addition to the use of a secondary rf discharge to predissociate the molecular iodine at the injection location near the supersonic laser cavity in an electric oxygen-iodine laser. A gain of 0.17 % cm^{-1} was obtained and the laser output power was 12.3 W in a stable cavity with two 99.990% reflective mirrors. The implementation of a combination of multiple smaller diameter discharge tubes plus the molecular iodine predissociator has permitted us to expand the flow conditions of the ElectricOIL device to higher pressures and flow rates. A continued expansion of the operating envelope to higher flow conditions, pressures, and gain length of the laser cavity, plus further improvements to the iodine dissociator are expected to provide significant increases to the gain and laser power. The results presented herein represent approximately an 80-fold improvement in gain and laser power that has been achieved since the initial demonstrations in 2004–2005.[1,2]

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