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Continuous-wave laser oscillation in subsonic flow on the 1315 nm atomic iodine transition pumped by electric discharge produced $O_2(a\,^1\Delta)$

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Herein the authors report on the demonstration of a continuous-wave laser in *subsonic* flow on the 1315 nm transition of atomic iodine using the energy transferred to $I(^2P_{1/2})$ from $O_2(a\,^1\Delta)$ produced by a radio-frequency-excited electric discharge. The electric discharge was sustained in an $O_2-He-NO$ gas mixture. Downstream of the discharge, cold gas injection was employed to raise the gas density and lower the temperature of the continuous gas flow to shift the equilibrium of atomic iodine in favor of the $I(^2P_{1/2})$ state. The laser output power was 540 mW in a stable cavity with two 99.993% reflective mirrors. © *2006 American Institute of Physics*.
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Oxygen-iodine laser systems[1] operate on the $I(^2P_{1/2}) \rightarrow I(^2P_{3/2})$ (hereafter denoted I^* and I, respectively) electronic transition of the iodine atom at 1315 nm. The population inversion is produced by the near resonant energy transfer between the excited singlet oxygen molecule $O_2(a\,^1\Delta)$ [also denoted $O_2(^1\Delta)$ hereafter] and the atomic iodine ground state. There are many system issues having to do with weight, safety, and operational logistics in the production of the $O_2(^1\Delta)$ by chemical means which have motivated investigations into methods to produce significant amounts of $O_2(^1\Delta)$ using flowing electric discharges. Several investigations have been conducted into the possibility of a continuous flow hybrid electrically powered oxygen-iodine laser (ElectricOIL) with electric discharges to produce the $O_2(^1\Delta)$.[2–9] These studies have shown that flowing oxygen containing mixtures, typically diluted with a rare gas, through electric discharges can produce quantities of $O_2(^1\Delta)$ that can be sufficient for lasing. Recent experimental studies using electric discharges have demonstrated $O_2(^1\Delta)$ yields (defined as $Y=O_2(^1\Delta)/[O_2(^3\Sigma)+O_2(^1\Delta)]$) greater than 15% using electric discharges.[5–9] The first demonstrations of gain in an ElectricOIL system were made in a fast supersonic flow cavity,[10,11] and were followed by the first demonstration of gain in slow subsonic flow.[12] The successful gain experiments were then followed by ElectricOIL power demonstrations in a supersonic flow cavity.[13,14]

Several modeling studies[4,7,8,15,16] have also been performed for these discharge driven oxygen-iodine laser systems. The measured yields of $O_2(^1\Delta)$ of >0.16 at reasonable pressures of >10 Torr and the ability to minimize the deleterious deactivation of I^* by atomic oxygen through the use of NO and or NO_2 (Ref. 11) suggested that the simple injection of cold N_2 would lower the temperature sufficiently to lead to positive gain and lasing in subsonic flow. Postdischarge modeling[16] supported that it may be possible to obtain high enough gain for lasing in a flowing subsonic arrangement after cold N_2 injection. Two of the advantages of slower flowing subsonic systems are as follows: (i) the number densities of $I(^2P_{1/2})$ and $O_2(^1\Delta)$ are higher than with supersonic expansion and (ii) stimulated emission can extract more of the excited state energy by virtue of the longer residence time which the excited species spend within the optical resonator.[17] Such considerations motivated this effort to obtain laser power in a subsonic ElectricOIL system.

A block diagram of the experimental setup is shown in Fig. 1. A radio frequency (rf) electric discharge at 13.56 MHz operating between two internal hollow cathode electrodes was used as the excitation source. The plasma zone was approximately 4.9 cm in diameter and 25 cm in length. Details of the performance of the electric discharge can be found in Ref. 5.

The subsonic cavity has a $2.54\times5.08\ \mathrm{cm}^2$ cross section flow channel with ports that can be used to measure gain, proportional to $[I(^2P_{1/2})]-0.5[I(^2P_{3/2})]$, or laser power when mirror mounts are attached. Measurements of the optical emission from $O_2(^1\Delta)$ at 1268 nm were made at the flow tube diagnostic duct upstream of the I_2 injection position. A Roper Scientific optical multichannel analyzer (OMA-V) with a 512-element InGaAs LN_2 cooled array interfaced to an Acton Research SP-150 monochromator was used for measurements at 1268 nm.

Micromotion 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

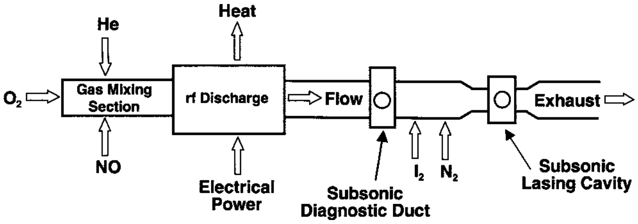

FIG. 1. Schematic of the experimental apparatus.

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absorption of molecular iodine at 488 nm. Details of this diagnostic are described by Rawlins *et al.*[18] Pressure in the flow tube and subsonic laser cavity 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.[19] The ISD is a diode laser based monitor for the small signal gain in iodine lasers and 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 subsonic flow cavity. The translational temperature in the flow is determined from the Doppler component of the Voigt profile.

The windows on the sides of the cavity when using the gain diagnostic were wedged and antireflection coated to minimize étalon effects. A two-pass configuration (10 cm path length) for the gain diagnostic was used in the subsonic flow. Measurements of the $O_2(^1\Delta)$ yield were obtained with the OMA-V and previous calibrations from gain measurements and the relative values of the spectral intensities measured for $I(^2P_{1/2})$ to $O_2(^1\Delta)$ using techniques originally developed by Hager[20] and Rawlins *et al.*[18]

Laser power measurements were made with a Scientech Astral™ model AC2500/AC25H calorimeter interfaced to a Scientech Vector™ model S310 readout and were made at the same location in the subsonic laser cavity as were the gain measurements. After the gain measurements were conducted, vacuum mirror mounts were then put in place for the laser power trials. Two mirrors with 1 m radius of curvature, purchased from AT Films (ATF), formed a stable optical cavity. Measurements of transmission T indicated a transmission of $0.005\% \pm 0.001\%$. Direct measurements of mirror reflectivity R and absorption/scattering AS were unavailable, but previous reflectivity measurements of similar mirrors indicated that a fraction of the remainder of $1-T$ is in AS losses for similar high reflectivity mirrors. Thus, we estimate that the mirrors each had a reflectivity of $99.993\% \pm 0.001\%$. The mirrors were separated by approximately 38 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.

Electric discharge stability and temperature control were found for be critical parameters for obtaining gain in previous experiments.[10,11] Electric discharges sustained in moderate pressures (5–15 Torr) of rare gas plus oxygen are prone to arcing and constriction. This issue coupled with the production of O atoms, O_3, and other excited species by the discharge adds higher levels of complexity to the downstream kinetics than are usually encountered in the purely chemical system. The critical aspect of temperature control results from the equilibrium of the pumping reaction

$$O_2(^1\Delta) + I(^2P_{3/2}) \leftrightarrow O_2(^3\Sigma) + I(^2P_{1/2}), \qquad (1)$$

where the forward rate is 7.8×10^{-11} cm^3/molecule s,[21] and the backward rate is $1.04 \times 10^{-10} \times \exp(-403/T)$ cm^3/molecule s.[22] The equilibrium rate constant ratio of the forward to backward reactions is $K_{\mathrm{eq}} = 0.75 \exp(403/T)$],[22] where T is the gas temperature. The yield of $O_2(^1\Delta)$ for optical transparency as a function of temperature is $Y_{\mathrm{OT}} = 1/[1 + 1.5 \exp(403/T)]$.[23] Note that as the temperature is reduced, K_{eq} becomes larger and Y_{OT} becomes smaller. Both are advantageous for laser oscillation.

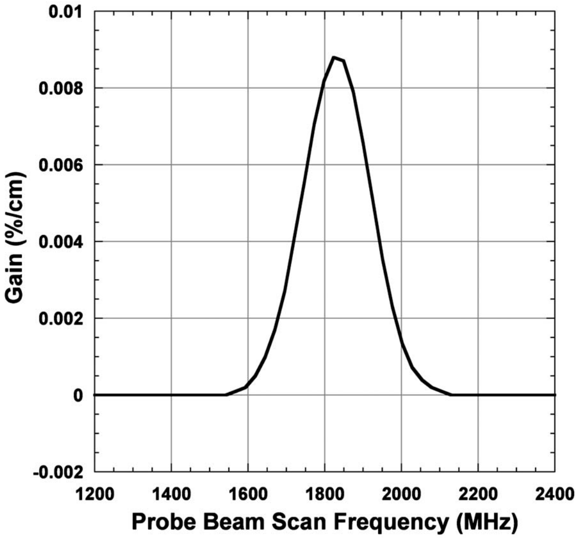

FIG. 2. Digitally filtered gain signal in the subsonic cavity as a function of probe beam scan frequency measured prior to lasing experiments.

The discharge flow conditions used in these experiments were 3.0 mmol/s of O_2 mixed with 16.0 mmol/s of He and 0.15 mmol/s of NO flowing through the rf discharge at 12.5 Torr. A secondary stream of $\approx$0.014 mmol/s of I_2 with 2.0 mmol/s of secondary He diluent was injected 64.8 cm downstream from the exit of the discharge. A tertiary flow of $\approx$185 mmol/s of cold N_2 gas ($\approx$88 K) was injected further downstream to lower the temperature and to raise the pressure. A purge flow of 20 mmol/s of He was used with the laser mirror mounts. The pressures in the discharge flow tube and in the subsonic laser cavity were 12.5 and 8.4 Torr, respectively. The pressure ratio indicates that the flow was approximately Mach 0.80 in the subsonic laser cavity.

Gain for the above flow conditions at 500 W of rf discharge power is shown in Fig. 2 and peaks at 0.009% cm^{-1} at line center. The line shape indicates a temperature of $\approx$180 K. The laser resonator was subsequently installed around the subsonic cavity. Laser power and $O_2(^1\Delta)$ yield measurements were made as a function of rf discharge power, as shown in Fig. 3. For the above flow conditions and 500 W rf power, a laser output power of 540 mW was obtained. For approximately the same flow conditions, rf power, and laser mirrors, 260 mW was obtained with a supersonic laser cavity;[14] therefore, the subsonic cavity demonstrated significant energy extraction advantages over a supersonic cavity due to higher number densities and longer residence time in the resonator. The yield of $O_2(^1\Delta)$ was $\approx$19% with a temperature of $\approx$435 K in the flow tube diagnostic duct. [Note that the drop in $O_2(^1\Delta)$ signal beyond 500 W is believed to be a consequence of instabilities and thermal constriction that visibly develop in our existing discharge under these flow conditions.[11]] The beam shape was circular with a diameter of $\approx$1.9 cm, the same as the clear aperture of the mirror mounts.

The threshold for laser oscillation lasing occurs at 135 W of rf discharge power with an estimated $O_2(^1\Delta)$ yield of $\approx$9% in the subsonic flow tube, as shown in Fig. 3. Note that there is a rolloff in laser power beyond 500 W that is

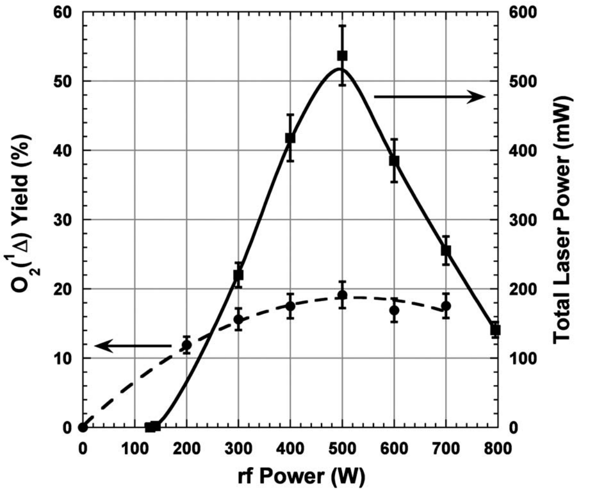

FIG. 3. $O_2(^1\Delta)$ yield in the flow tube diagnostic section and total laser power in the subsonic cavity as a function of rf discharge power.

more rapid than the drop in $O_2(^1\Delta)$ yield which is in part attributed to discharge instabilities.[11] Even in the absence of discharge instabilities, laser oscillation would likely decrease at higher powers for these conditions as a consequence of two additional factors: (i) higher powers result in higher gas temperatures and consequently lower gain and (ii) progressively more O atoms are generated at higher powers while the NO flow rate was optimized for 450 W. [O atoms have been found to quench the excited $I(^2P_{1/2})$ atom[10–12,24]]. For reference, the first measurement of laser action using an electrically driven oxygen-iodine laser with a supersonic laser cavity at ≈1.3 Torr produced 220 mW.[13]

In conclusion, cw laser action was measured in subsonic flow on the $I(^2P_{1/2}) \rightarrow I(^2P_{3/2})$ electronic transition of the iodine atom at 1315 nm pumped by a near resonant energy transfer from $O_2(^1\Delta)$ produced in an electric discharge. Cold N_2 was injected to lower the temperature of the flow and shift the equilibrium of atomic iodine in favor of the $I(^2P_{1/2})$ state. This produced sufficient population inversion to observe gain of $\approx 0.009\%\ \mathrm{cm}^{-1}$ followed by laser oscillations when two ≈99.993% reflectivity mirrors were used to form an optical resonator surrounding the gain medium. The peak laser output power in these experiments was 540 mW.

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