

# Path to the Measurement of Positive Gain on the 1315-nm Transition of Atomic Iodine Pumped by $O_2(a^1\Delta)$ Produced in an Electric Discharge

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**Abstract**—Laser action at 1315 nm on the  $I(^2P_{1/2}) \rightarrow I(^2P_{3/2})$  transition of atomic iodine is conventionally obtained by a near-resonant energy transfer from  $O_2(a^1\Delta)$  which is produced using wet-solution chemistry. The system difficulties of chemically producing  $O_2(a^1\Delta)$  have motivated investigations into gas phase methods to produce  $O_2(a^1\Delta)$  using low-pressure electric discharges. In this paper, we report on the path that led to the measurement of positive gain on the 1315-nm transition of atomic iodine where the  $O_2(a^1\Delta)$  was produced in a flowing electric discharge. Atomic oxygen was found to play both positive and deleterious roles in this system, and as such the excess atomic oxygen was scavenged by  $NO_2$  to minimize the deleterious effects. The discharge production of  $O_2(a^1\Delta)$  was enhanced by the addition of a small proportion of NO to lower the ionization threshold of the gas mixture. The electric discharge was upstream of a continuously flowing supersonic cavity, which was employed to lower the temperature of the flow and shift the equilibrium of atomic iodine more in favor of the  $I(^2P_{1/2})$  state. A tunable diode laser system capable of scanning the entire line shape of the (3,4) hyperfine transition of iodine provided the gain measurements.

**Index Terms**—Chemical oxygen–iodine laser (COIL), discharge oxygen–iodine laser (DOIL), ElectriCOIL, RF excitation of oxygen, singlet-delta oxygen.

## I. INTRODUCTION

THE classic chemical oxygen–iodine laser (COIL) system [1] operates on the  $I(^2P_{1/2}) \rightarrow I(^2P_{3/2})$  (hereafter denoted as  $I^*$  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 metastable excited singlet oxygen molecule  $O_2(a^1\Delta)$  (denoted  $O_2(a)$  hereafter) and the iodine atom ground state  $I$ . Conventionally, a two-phase (gas–liquid) chemistry singlet oxygen generator (SOG) produces the  $O_2(a)$ . There are many system issues having to do with weight, safety, and the ability to rapidly modulate the production of the  $O_2(a)$  which have motivated investigations into methods to produce significant amounts of  $O_2(a)$  using

flowing electric discharges. Early attempts to implement electric discharges to generate  $O_2(a)$  and transfer energy to iodine to make a laser by Zaleskii [2] [29] and Fournier [3] did not result in positive gain. Several investigations have been conducted into the possibility of a continuous-flow hybrid electrically powered oxygen–iodine laser with electric discharges to produce the  $O_2(a)$  [4]–[9]. These studies have shown that flowing electric discharges through oxygen containing mixtures, typically diluted with a rare gas, can produce useful quantities of  $O_2(a)$ . Recent studies have demonstrated  $O_2(a)$  yields greater than 15% using electric discharges [6], [7], [9], and modeling results [4], [7], [8], [10] have indicated that such a system may produce a viable laser. In this paper, we detail the investigation that led to our recently reported measurements of positive gain [11] on the  $I^* \rightarrow I$  electronic transition of the iodine atom at 1315 nm pumped by resonance excitation transfer from  $O_2(a)$  produced in an electric discharge.

## II. EXPERIMENTAL SETUP

A block diagram of the flow tube setup is shown in Fig. 1. A radio frequency (RF) discharge between two internal hollow cathode electrodes (each 13 cm long) operating at 13.56 MHz was used as the excitation source. The plasma zone is approximately 4.9 cm in diameter and 25 cm long. Details of the performance of a similar electric discharge with capacitive external electrodes can be found in [5]. The subsonic diagnostic duct has four windows through which simultaneous measurements are made of the optical emission from  $O_2(a)$  at 1268 nm,  $O_2(b^1\Sigma)$  (denoted  $O_2(b)$  hereafter) at 762 nm,  $I^*$  at 1315 nm, and the gain/absorption proportional to  $\{[I^*] - 0.5 \cdot [I]\}$ . A Roper Scientific Optical Multi-channel Analyzer (OMA-V) with a 512-element InGaAs  $LN_2$  cooled array, attached to a monochromator (Acton Research SP-150), was used for the spectral measurements at 1268 and 1315 nm. A CCD camera (Santa Barbara Instruments Group, Inc. ST-6) coupled to a monochromator (Jarrell Ash M10 023 100) was implemented to measure the emission of  $O_2(b)$  at 762 nm. The supersonic diagnostic cavity is a Mach-2 nozzle with view port windows.

A variety of Micro-Motion CMF and Omega FMA mass flow meters were used to accurately measure the flow rates of the gases. A pair of Micro-Motion CMF-025s were used to measure the  $O_2$  and Ar flow rates, a Micro-Motion CMF-010 to measure the primary He flow rate, an Omega FMA3109 to measure the NO flow, an Omega FMA3108 to measure the secondary He

Manuscript received June 22, 2004; revised October 7, 2004. This work was supported by the Air Force Office of Scientific Research and the U.S. Army Space and Missile Defense Command.

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Digital Object Identifier 10.1109/JQE.2004.839691

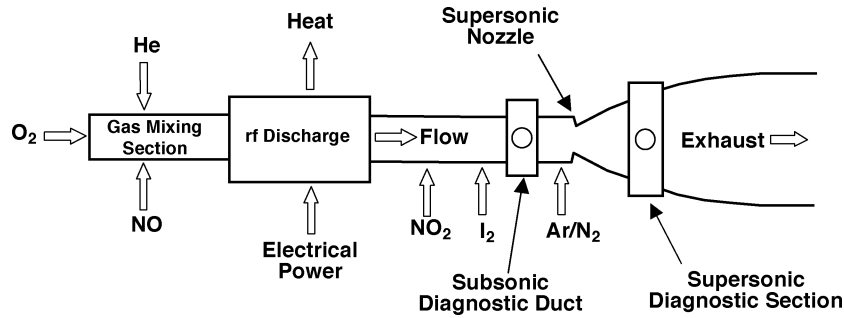


Fig. 1. Schematic of the experimental apparatus.

flow that carries the  $I_2$ , and an Omega FMA3107 to measure the  $NO_2$  flow. A diagnostic developed by Physical Sciences Inc. (PSI) was used that is based upon the continuum absorption of molecular iodine at 488 nm to measure the  $I_2$  flow. Details of this diagnostic are described by Rawlins *et al.* [12]. Pressures in the subsonic and supersonic flow regions were measured by capacitance manometers from MKS (model 124AA-00 100AB-S) and Leybold (model CM10). Incident and reflected powers from the RF matching network were measured by a Bird Thruline model 43 wattmeter (RF “System Power” is the difference of the incident and reflected powers).  $V-I$  characteristics for an estimation of  $E/N$  were taken with a Tektronix P6015 voltage probe and a Pearson Model 480 current monitor (note that  $V-I$  measurements were made for only the cases reported in Fig. 11 of this work and that  $E/N$  was computed using the method outlined [5]).

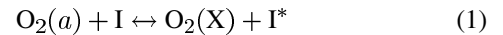
Measurements of gain (or absorption) were made with the Iodine-Scan diagnostic (ISD), developed by PSI [13]. The ISD is a diode laser-based monitor for the small-signal gain in iodine lasers. The system uses a single-mode tunable diode laser that is capable of accessing all six hyperfine components of the atomic iodine transition. It was calibrated in frequency for 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 both the subsonic portion of the flow tube and in the supersonic cavity. Since the ISD uses a narrow-band diode laser, the measured lineshapes can also be used to determine the local temperature from the Voigt profile.

Wedge antireflection-coated windows were used on the sides of both the subsonic diagnostic section and the supersonic cavity for the gain diagnostic to minimize etalon effects. A two-pass configuration (10-cm path length) was used in the subsonic section and a four-pass configuration (20-cm path length) in the supersonic section. Yield measurements of  $O_2(a)$  were made from the gain diagnostic and relative  $I^*$  to  $O_2(a)$  spectral intensity measurements based upon the techniques originally developed by Hager [14] and Davis and Rawlins [12].

### III. EXPERIMENTAL RESULTS

During the course of this research, it was determined that electric discharge stability and temperature control are critical parameters to obtaining positive gain. Electric RF discharges sustained in moderate pressures (many to tens of torr) of oxygen

are prone to instabilities. The discharge production of O atoms,  $O_3$ , and other excited species adds higher levels of complexity to the downstream kinetics when the iodine donor species are added to the flow which are not encountered in a purely chemical generation system. The critical aspect of temperature control results from the equilibrium of the pumping reaction



where the forward rate is  $7.8 \times 10^{-11}$  cm<sup>3</sup>/molecule-s [15], and the backward rate is  $1.04 \times 10^{-10} \exp(-403/T)$  cm<sup>3</sup>/molecule-s [16], with the equilibrium rate constant ratio of the forward to backward reactions being  $K_{eq} = 0.75 \exp(403/T)$  [16], where  $T$  is the gas temperature. The threshold yield of  $O_2(a)$  for positive  $I^*$ -to- $I$  inversion as a function of temperature can be written as  $Y_{th} = 1/[1 + 1.5 \exp(403/T)]$  [17]. Note that the backward rate is slower,  $K_{eq}$  is larger, and  $Y_{th}$  is lower as  $T$  is decreased.

We had previously been unsuccessful in attaining positive gain (as had other groups, see Section I) despite having achieved yields of  $O_2(a)$  with an electric discharge that were, in principle, high enough to do so. Recently, we conducted experiments that have led to the attainment of positive gain, and we describe these experiments below. We were observing absorption in the supersonic region with temperatures of approximately 240 K, despite having yields that we believed were approximately 15%, which should have been well over the required threshold yield  $Y_{th}$  of  $O_2(a)$  required for positive gain. As such, we began a rigorous investigation of the effects of iodine in the subsonic flow region without the added complication of the supersonic cavity. To perform these experiments, we moved the iodine injection point upstream (approximately 20 cm) of a diagnostic section added into the subsonic flow tube (Fig. 1). Previously we had been injecting the iodine just upstream of the nozzle throat as in traditional COIL geometries.

We made simultaneous measurements of the optical emission from  $O_2(a)$  at 1268 nm,  $O_2(b)$  at 762 nm,  $I^*$  at 1315 nm, and the absorption through the optical windows in the subsonic diagnostic section. The initial 1268-nm emission measurements are illustrated in Fig. 2; the other results are shown later. Two important things are immediately apparent from these data. First, for the zero iodine case there is a drop in the 1268-nm signal that begins at around 500 W. (Note that RF system power is presented; electrical measurements indicate that approximately 80%–90% of the system power is actually absorbed by the plasma for the  $O_2 : He = 1 : 4$  mixtures we ran in these experiments.)

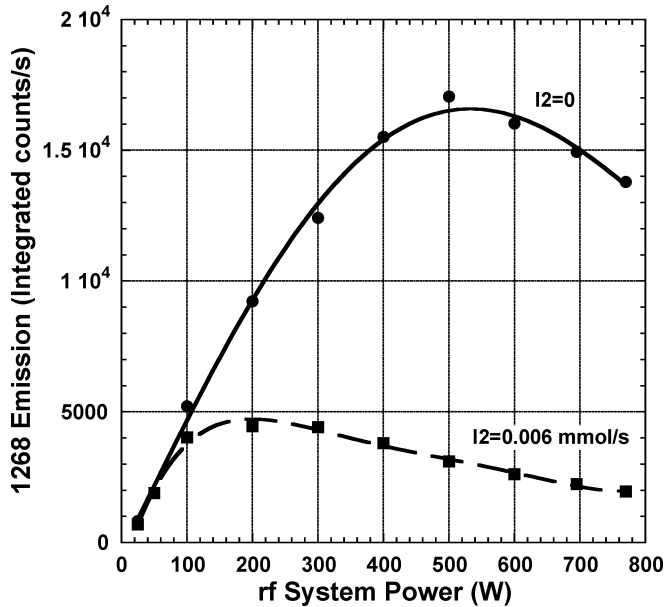


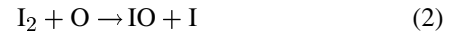
Fig. 2.  $O_2(a)$  emission at 1268 nm with and without iodine at the subsonic diagnostic port as a function of system power, for a flow of 4 mmol/s of  $O_2$  mixed with 16 mmol/s of He at a pressure of 10 torr.

This drop in signal is believed to be a consequence of instabilities and thermal constriction that visibly develop in our existing discharge under these flow conditions. We are presently investigating the discharge stability issues in an effort to improve the performance and yield of the discharge, but will not discuss this issue further in this paper. The second and more troubling observation from Fig. 2 is that, when very small amounts of molecular iodine were added to the flow, the level of  $O_2(a)$  emission at 1268 nm dropped dramatically. The flow rate of  $O_2$  was 4 mmol/s with an estimated  $O_2(a)$  yield of 15% at 500 W of RF power, therefore there should be approximately 0.6 mmol/s of  $O_2(a)$ . The iodine flow rate was approximately 0.006 mmol/s, i.e., only 1% of the  $O_2(a)$  concentration. Given that the molecular iodine was only 1% of the  $O_2(a)$  and that the O atoms should rapidly dissociate it [4], the dramatic drop in the 1268-nm signal could not be explained by the classic COIL iodine dissociation process. Furthermore, the concentration of atomic iodine, approximately 2% of the  $O_2(a)$ , was far too low to explain a significant drop in  $O_2(a)$  from the pumping reaction. These facts lead us to the suggestion that whatever phenomenon is causing this dramatic drop in  $O_2(a)$  may also be the primary reason why we (and others) have been previously unsuccessful in attaining positive gain with such electrically pumped systems. Furthermore, it leads to the point that, while measurements of high yields in pristine environments of a rare gas plus  $O_2$  and the various other oxygen species from a discharge are encouraging, the issue of greater significance is the yield in the presence of iodine at high enough densities to be of interest.

Given the successful history of COIL where the change in yield in the presence of iodine is negligibly small, the different character with this electrically pumped system is related to products of the discharge that are not present in classic COIL, i.e., products other than  $O_2(a)$  and  $O_2(b)$ . Since the loss behavior occurs only with iodine present, it is believed that the loss must

be through the  $I^*$  channel, i.e., energy transfers through  $I^*$  from  $O_2(a)$  to some other species or into heating the gas. Various candidates are: O atoms,  $O_3$ , charged species, ultraviolet (UV), or vacuum UV (VUV) radiation. All could play a deleterious role and none appear in a classic COIL. The most obvious candidate is atomic oxygen as it is present in number densities on the order of the  $O_2(a)$ . Modeling predicts that ozone is in quantities of two to three orders of magnitude lower than  $O_2(a)$  [4], [10], and the charged species become negligible within a few centimeters downstream of the exit of the discharge [10], so these candidates seem less likely to be the major cause of the observed  $O_2(a)$  loss. The fact that our discharge and flow tube sections are colinear allows radiation emitted in the discharge to be observed downstream, so it is conceivable that UV and VUV are playing some role, but the magnitude of this effect seems less likely to be a major contributor. As such, we focused in on oxygen atoms as being the major contributor to the deleterious loss of  $O_2(a)$  when iodine was present.

Oxygen atoms play a positive role as well as a potential deleterious role in the kinetics downstream of the discharge region with iodine present. Their positive role is that they rapidly dissociate molecular iodine through the following processes:



The rates for reactions (2) and (3) are  $1.4 \times 10^{-10}$  cm<sup>3</sup>/molecule-s [18], and  $1.5 \times 10^{-10}$  cm<sup>3</sup>/molecule-s [18], respectively. The potential deleterious role of oxygen atoms was first postulated by Heaven [19] to be



Han *et al.* [20] have recently estimated this rate to have an upper bound of  $2 \times 10^{-12}$  cm<sup>3</sup>/molecule-s; this is considerably smaller (an order of magnitude or more) than both the forward and backward rates of reaction (1), and hence this reaction was originally thought to be of limited importance in reasonably fast flowing systems such as our setup. There is presently no known temperature dependence for reaction (4). However, of the candidate processes listed for the dramatic loss of  $O_2(a)$  in the presence of iodine, atomic oxygen seemed the most likely culprit, and, as such, experiments were performed to test its effects.

We established the O atom production from the discharge as a function of power into the discharge by titrating with  $NO_2$  using a well-established technique first developed by Kaufman [21]. For these experiments, the  $NO_2$  was injected 50 cm downstream of the downstream electrode. A mixture of 4 mmol/s of  $O_2$  and 16 mmol/s of He was run through the RF discharge at a pressure of approximately 10 torr ( $O_2$  partial pressure of 2 torr). Fig. 3 shows approximately a linear dependence of O atom production with discharge power; this linear behavior is consistent with previous modeling work in the range in which we are operating [10]. At 300 W of system power, Fig. 3 shows an O atom flow rate of 0.25 mmol/s or approximately an O atom yield of 6.3%.

For comparison with pure oxygen data taken in [5] (similar to this setup in terms of the discharge and subsonic flow tube), an O atom titration was run for a 5-mmol/s pure oxygen flow

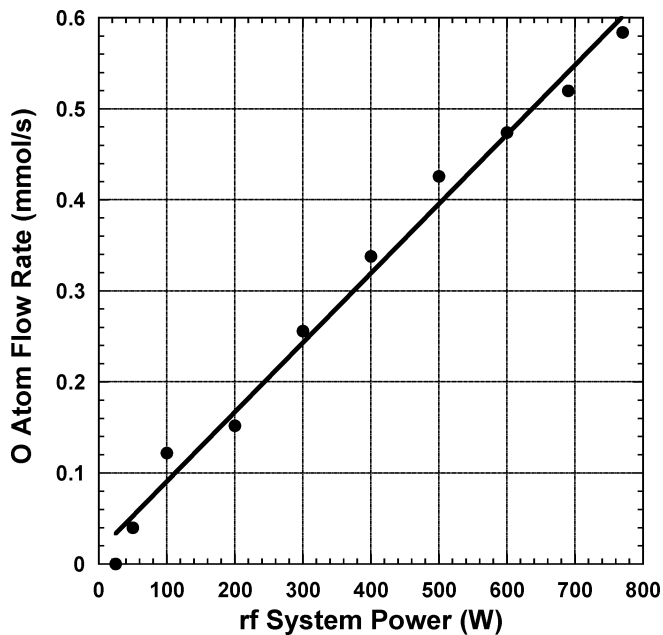


Fig. 3. Oxygen atom titration measurements as a function of system power for a flow of 4 mmol/s of  $O_2$  mixed with 16 mmol/s of He at a pressure of 10 torr.

at 2.3 torr. This measurement gave an atomic oxygen yield of only 2.8% at an injection point 58.4 cm downstream of the exit of the discharge at a system power of 300 W (which corresponds to an absorbed power of approximately 265 W in the pure oxygen case). Interestingly, the 6.3% O atom yield for this helium diluted case is more than a factor of two higher than the pure oxygen case. It should be noted that measurements taken in [5] showed approximately a factor of two higher  $O_2(a)$  signals with the helium diluted case as compared to the pure oxygen case. Hence, this type of rf discharge, at these pressures and flow conditions, produces higher yields of both  $O_2(a)$  and O when diluted by helium.

We then added  $NO_2$  upstream of the iodine ring injector and monitored the emission at 1268, 1315, and 762 nm at the subsonic diagnostic section. Figs. 4–7 show the dramatic changes that occur as the flow rate of  $NO_2$  is increased. Note that, as  $NO_2$  was added, the pressure in the discharge region was maintained at approximately 10 torr by adjusting a downstream flow rate of Ar (see Fig. 1). Fig. 4 clearly shows how increasing the  $NO_2$  flow raises the 1268-nm signal in the presence of iodine progressively to approximate the signal with no iodine in the flow, i.e., by scavenging O atoms from the flow, there is a progressively lesser effect from process (4). However, the situation is more complex than just that. Note that the point where we are almost back to the nominal 1268-nm signal occurs at an  $NO_2$  flow rate of 1.0 mmol/s, yet the O atom flow at 770 W is only approximately 0.59 mmol/s (see Fig. 3). This result was unexpected since the  $NO_2$  flow rate is well beyond the full titration point, i.e., where  $[NO_2] = [O]$  at the highest system power level. Since our mixing appears to be visibly complete within a few centimeter and the  $O + NO_2$  reaction rate is fairly fast, approximately  $1 \times 10^{-11} \text{ cm}^3/\text{molecule}\cdot\text{s}$  at room temperature [22], we presently do not understand why we must significantly overtitrate the atomic oxygen to regain the majority of the  $O_2(a)$

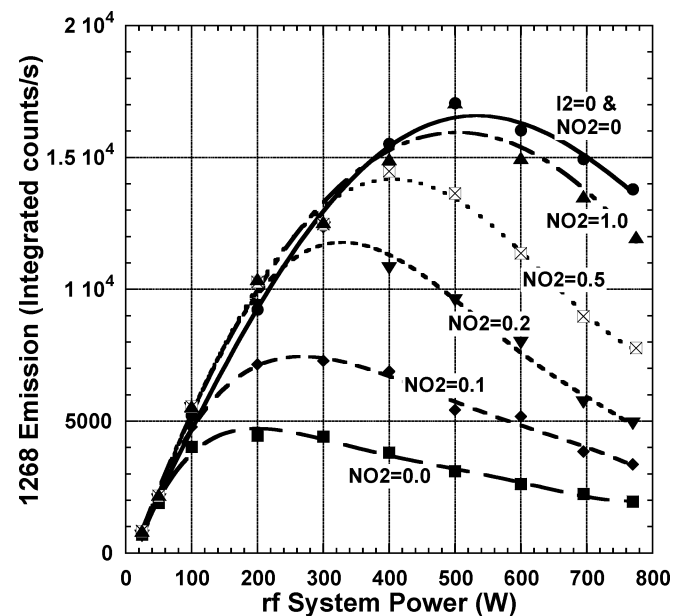


Fig. 4.  $O_2(a)$  emission at 1268 nm with and without iodine at the subsonic diagnostic port as a function of system power and the  $NO_2$  flow rate, for a flow of 4 mmol/s of  $O_2$  mixed with 16 mmol/s of He at a pressure of 10 torr.  $NO_2$  flow rates are in mmol/s.

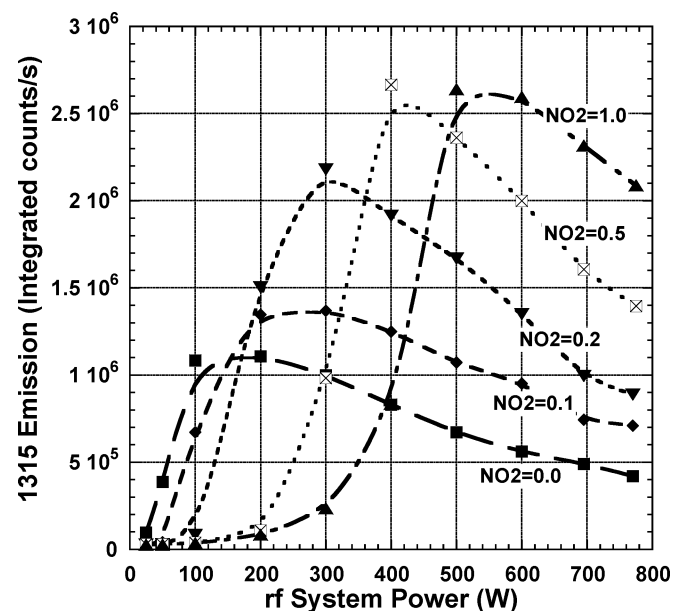


Fig. 5.  $I^*$  emission at 1315 nm at the subsonic diagnostic port as a function of system power and the  $NO_2$  flow rate, for a flow of 4 mmol/s of  $O_2$  mixed with 16 mmol/s of He at a pressure of 10 torr.  $NO_2$  flow rates are in mmol/s.

signal; we suspect that there may be some other process(es) occurring that we have not yet identified nor understood.

Fig. 5 illustrates the progressive rise in the  $I^*$  emission with increasing  $NO_2$  flow rate. This rise is consistent with the increasing  $O_2(a)$  signal shown in Fig. 4. It is of considerable interest that the location of the peak signal shifts to higher powers with higher  $NO_2$  flow rates. We believe that simultaneously competing effects explain the majority of this phenomenon. First, as the  $NO_2$  flow rate increases, the  $O_2(a)$  peak increases (and equivalently the yield) and shifts toward higher powers (see Fig. 4); as the yield of  $O_2(a)$  increases/decreases, then so

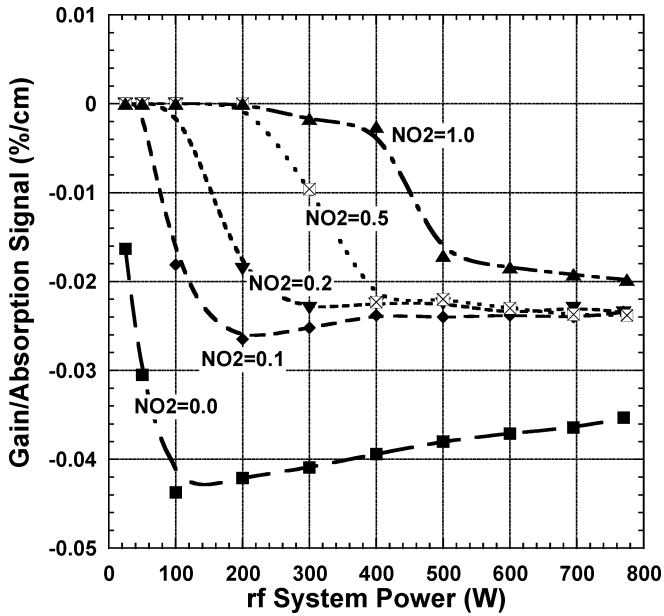
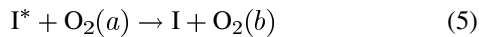


Fig. 6. Absorption at 1315 nm at the subsonic diagnostic port as a function of system power and the  $\text{NO}_2$  flow rate, for a flow of 4 mmol/s of  $\text{O}_2$  mixed with 16 mmol/s of He at a pressure of 10 torr.  $\text{NO}_2$  flow rates are in mmol/s.

should the observed  $\text{I}^*$  signal via the equilibrium of reaction (1). Note that the  $\text{O}_2(a)$  signal peaks around 500 W where the discharge instabilities begin to occur; this helps to explain why the  $\text{I}^*$  peak for the  $\text{NO}_2 = 1.0$  mmol/s case is similar to the  $\text{I}^*$  peak for the  $\text{NO}_2 = 0.5$  mmol/s case, both of which occur in the region where the discharge instabilities first occur. Second, at higher  $\text{NO}_2$  flow rates, the atomic oxygen is severely overtitrated and thus the iodine dissociation fraction (and available atomic iodine) is reduced. Fig. 6 shows a decrease in absorption with increasing  $\text{NO}_2$  flow rate. However, Fig. 6 also shows that there is no absorption observed at low power and high  $\text{NO}_2$  flow; this is indicative of very little atomic iodine and hence a very small iodine dissociation fraction for these overtitrated cases.

Fig. 7 shows the dramatic increase of the  $\text{O}_2(b)$  emission when  $\text{NO}_2$  is added. First note that, without  $\text{I}_2$  and without  $\text{NO}_2$ , the  $\text{O}_2(b)$  count rate is less than  $2 \times 10^4$  but increases by at least a factor of 5 when 0.008 mmol/s of  $\text{I}_2$  is added (at 400 W). We believe that this is due to a combination of atomic iodine formed by reactions (2) and (3) along with reaction (1) to produce  $\text{I}^*$  followed by



which has a reaction rate of  $1.0 \times 10^{-13} \text{ cm}^3/\text{molecule}\cdot\text{s}$  [23]. While this is a negligible loss to  $\text{O}_2(a)$ , it is a significant production rate of  $\text{O}_2(b)$ . When  $\text{NO}_2$  is added, the quenching of  $\text{O}_2(b)$  by the O atoms is reduced in proportion to the reduction of O atoms.

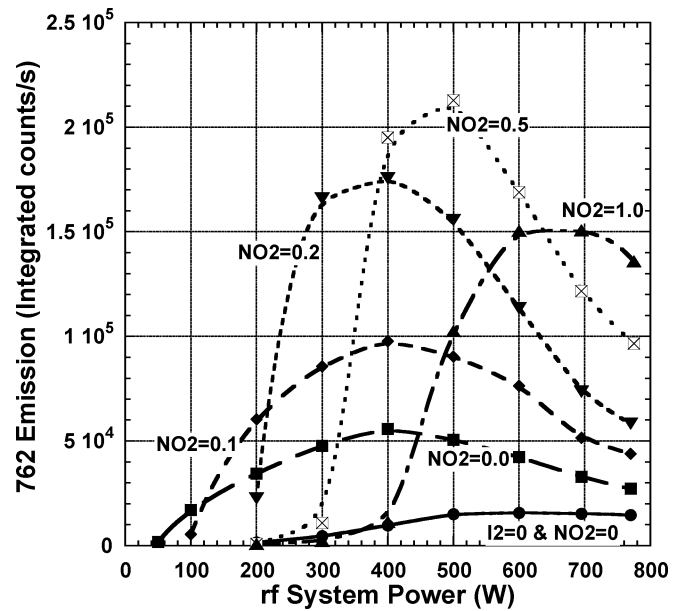
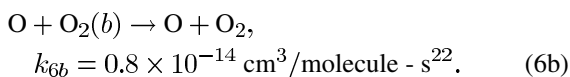
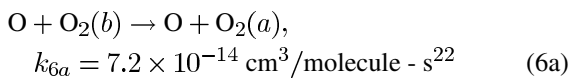


Fig. 7.  $\text{O}_2(b)$  emission at 762 nm with and without iodine at the subsonic diagnostic port as a function of system power and the  $\text{NO}_2$  flow rate, for a flow of 4 mmol/s of  $\text{O}_2$  mixed with 16 mmol/s of He at a pressure of 10 torr.  $\text{NO}_2$  flow rates are in mmol/s.

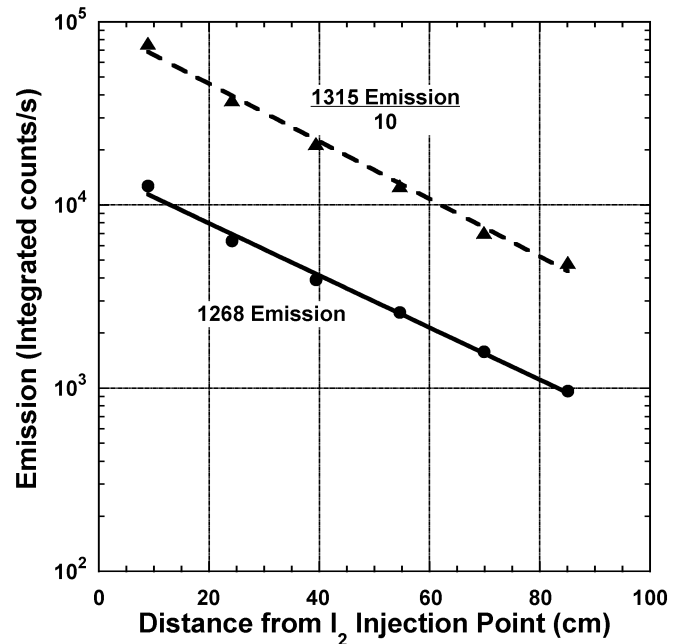


Fig. 8.  $\text{O}_2(a)$  (1268 nm) and  $\text{I}^*$  (1315 nm) emission versus distance from the  $\text{I}_2$  injection point for a primary discharge flow of 4 mmol/s of  $\text{O}_2$  mixed with 16 mmol/s of He at a pressure of 10 torr. A secondary flow of 0.008 mmol/s of  $\text{I}_2$  and 2 mmol/s of He was injected at  $x = 0$ . The RF power was 400 W. (Note that the 1315-nm emission signal has been divided by a factor of 10).

Also, the production of  $\text{O}_2(b)$  by reaction (5) is enhanced. The combination leads to a quadratic if not exponential growth in  $\text{O}_2(b)$  with increased power.

In an effort to establish a better estimate for the rate constant for reaction (4), the emissions of  $\text{O}_2(a)$  and  $\text{I}^*$  were monitored as a function of the distance from the plane of the  $\text{I}_2$  injection and is presented in Fig. 8. The data show that the two signals decay by a significant amount with a simple exponential decay.

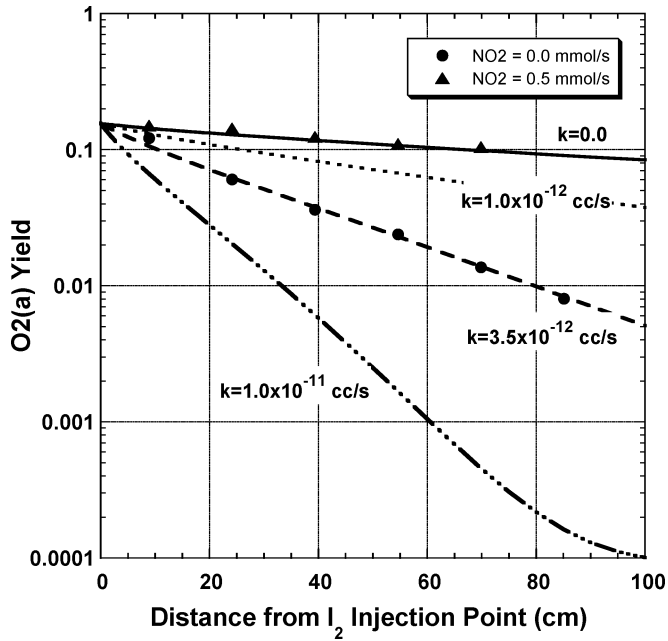


Fig. 9.  $O_2(a)$  yield versus distance from the  $I_2$  injection point. Experimental data are compared with Blaze II predictions for differing  $I^* + O$  reaction rates for a flow of 4 mmol/s of  $O_2$  mixed with 16 mmol/s of He at a pressure of 10 torr. A secondary flow of 0.008 mmol/s of  $I_2$  and 2 mmol/s of He was injected at  $x = 0$ . The RF power was 400 W. Data were taken without  $NO_2$  and with 0.5 mmol/s of  $NO_2$ .

Both appear to have the same approximate spatial decay rate, which is an indication of the near equilibrium between  $O_2(a)$  and  $I^*$  via the forward and backward rates associated with reaction (1).

It is shown in Appendix A that, with the data illustrated in Fig. 8 coupled with measurements of the oxygen atom concentration and the initial  $O_2(a)$  concentration determined by the technique outlined by Rawlins *et al.* [12], one can obtain a first-order estimate of the rate coefficient for the deactivation of  $I^*$  to I from (7) [(A-5) of Appendix A]

$$k_4 = \frac{[O_2(a)]_0}{[O]_0[I^*]_0} \cdot \frac{u_f}{L} \quad (7)$$

where  $u_f$  is the flow velocity and the subscript “0” indicates the concentration of the various species at the plane of iodine injection (with the assumption that the molecular iodine is dissociated immediately by the O atoms) with spatial variation of  $O_2(a)$  and  $I^*$  being  $\exp(-z/L)$  in agreement with Fig. 8. For the 10-torr case illustrated in Fig. 8 having an estimated  $O_2(a)$  yield of 15% (at the  $I_2$  injection point), a temperature of 375 K from the gain diagnostic and hence an equilibrium constant  $K_{eq} = 2.19$ , an oxygen atom density of  $3.72 \times 10^{15} \text{ cm}^{-3}$ , an  $O_2(a)$  concentration of  $6.70 \times 10^{15} \text{ cm}^{-3}$ ,  $[I] + [I^*]$  of  $1.86 \times 10^{14} \text{ cm}^{-3}$  and thus  $[I^*]$  of  $4.60 \times 10^{13} \text{ cm}^{-3}$  (from  $K_{eq}$  and an  $O_2(a)$  yield of 15%), a flow velocity of 2633 cm/s and  $L$  of 30.5 cm from Fig. 8 gives

$$k_4 = 3.4 \times 10^{-12} \text{ cm}^3/\text{molecule} \cdot \text{s} \quad (8)$$

which is higher than the upper bound of  $2 \times 10^{-12} \text{ cm}^3/\text{molecule} \cdot \text{s}$  estimated by Han *et al.* [20].

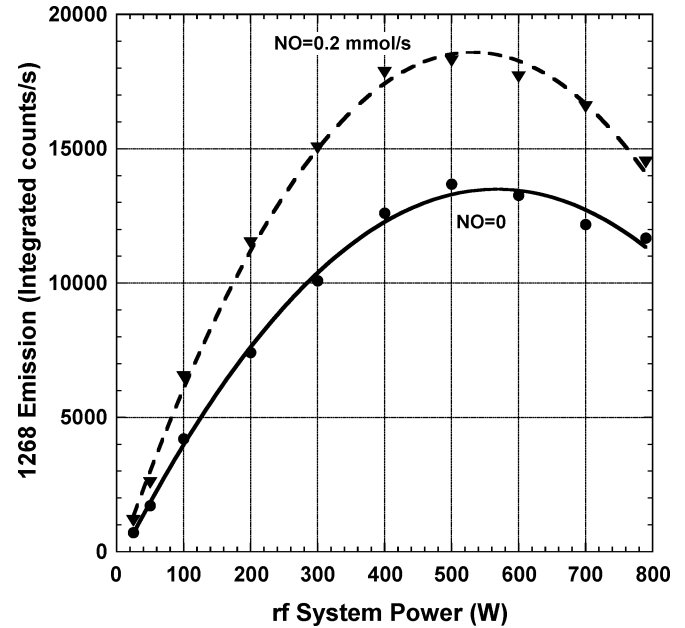


Fig. 10.  $O_2(a)$  emission at 1268 nm with and without NO at the subsonic diagnostic port as a function of system power, for a flow of 5 mmol/s of  $O_2$  mixed with 20 mmol/s of He at a pressure of 10 torr.

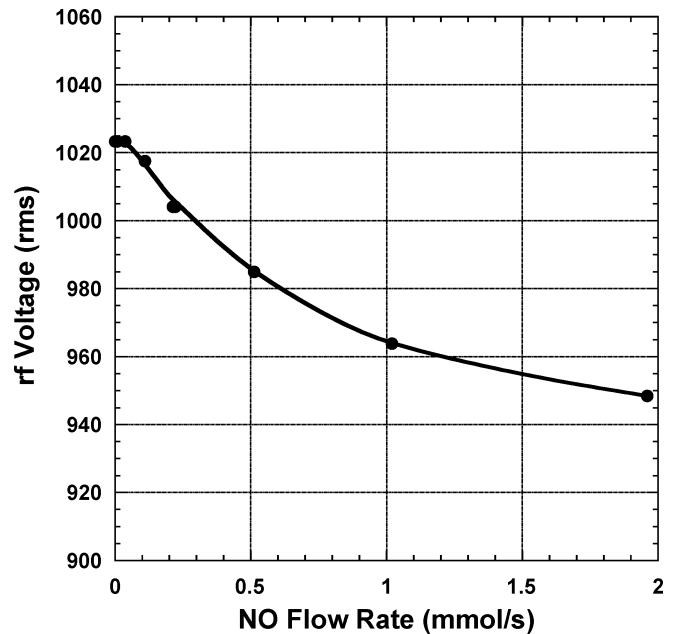


Fig. 11. Measured RF voltage as a function of the NO flow rate.

The simple exponential deactivation of  $O_2(a)$  and  $I^*$  suggests a simple deactivation process as expressed by reaction (4).

For another estimate (including all the known post-discharge kinetics), the  $O_2(a)$  data illustrated in Fig. 8 were converted to yield, and Blaze II [4], [24] simulations were run to determine an estimate of the  $I^* + O$  rate constant, Fig. 9. Experimental data were also taken for an overtitrated situation where the  $NO_2$  flow was 0.5 mmol/s (from Fig. 3, the O atom flow rate for these conditions was approximately 0.32 mmol/s) to simulate the case where the  $I^* + O$  rate was zero or, equivalently, when there are zero oxygen atoms. Fig. 9 indicates that the rate for  $I^* + O$  is

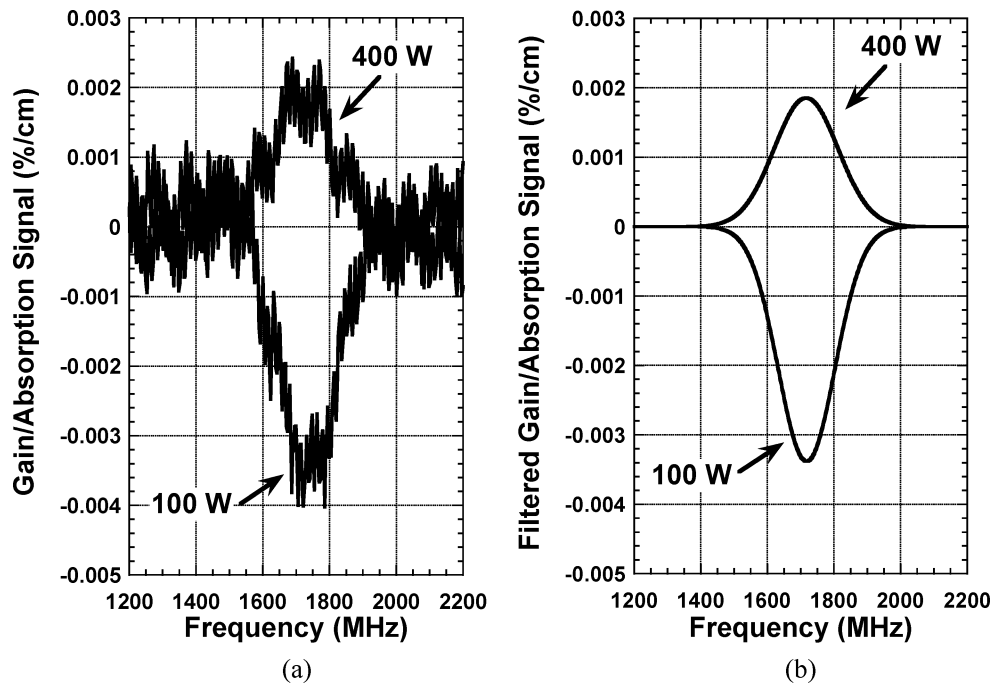


Fig. 12. Gain in the supersonic cavity as a function of frequency. (a) Raw signal. (b) Digitally filtered signal. Positive gain was observed at 400-W RF discharge power and absorption was observed at 100 W.

approximately  $3.5 \times 10^{-12} \text{ cm}^3/\text{molecule}\cdot\text{s}$ , which is significantly higher than the upper bound of  $2 \times 10^{-12} \text{ cm}^3/\text{molecule}\cdot\text{s}$  estimated by Han *et al.* [20]. Based upon our experiments and analyses, the rate for  $\text{I}^* + \text{O}$  appears to be approximately  $3.5 \times 10^{-12} \text{ cm}^3/\text{molecule}\cdot\text{s}$ . Since the measurement by Han *et al.* is a more direct measurement of the rate, it is currently believed that the estimate of  $3.5 \times 10^{-12} \text{ cm}^3/\text{molecule}\cdot\text{s}$  determined in this study may be representative of a more global loss mechanism that is still not fully understood. The fact that the Blaze prediction with a zero rate matches the overtitrated data reasonably well supports the conclusion that the presence of O atoms in the flow is not helpful when atomic iodine is also present; however, this still does not mean that the  $\text{I}^* + \text{O}$  process [reaction (4)] is the only significant loss mechanism.

Other possible quenchers of  $\text{I}^*$  that have been considered are  $\text{NO}_2$ , NO, IO, and  $\text{O}_3$ . The  $\text{I}^* + \text{NO}_2$  rate was measured to have an upper bound of  $8.5 \times 10^{-14} \text{ cm}^3/\text{molecule}\cdot\text{s}$  [20], and the rate by NO is  $1.2 \times 10^{-13} \text{ cm}^3/\text{molecule}\cdot\text{s}$  [25], but neither of these rates is large enough to compete with the  $\text{I}^* + \text{O}$  quenching rate. Further, if NO were a significant quencher of  $\text{I}^*$ , then we would expect to see a more pronounced quenching effect as the  $\text{NO}_2$  titration flow rate was increased (NO and  $\text{O}_2$  are the products of the  $\text{NO}_2 + \text{O}$  titration reaction); therefore we do not believe that NO is of significance as an  $\text{I}^*$  quencher for these gas mixture and flow conditions. The IO self removal reaction  $\text{IO} + \text{IO} \rightarrow 2\text{I} + \text{O}_2$  is fast,  $8.2 \times 10^{-11} \text{ cm}^3/\text{molecule}\cdot\text{s}$  [20], but the predicted concentrations are too small for IO to play any significant role in quenching  $\text{I}^*$ . The quenching rate of ozone is not known, but, based upon predicted concentrations, the quenching rate with ozone would have to be two orders of magnitude larger than the quenching rate of O for the ozone reaction to compete. It is also possible that the sum of the effects of lesser quenchers is adding up to a level that competes with the O atoms; further

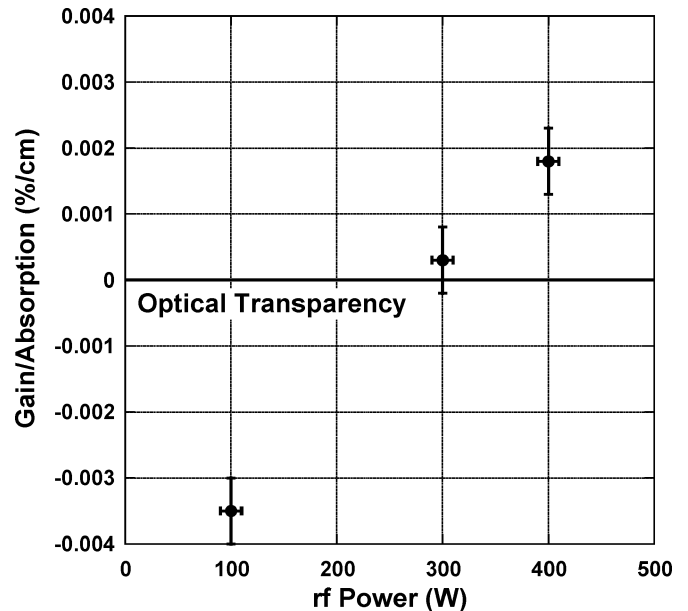


Fig. 13. Gain in the supersonic cavity as a function of RF discharge power.

studies need to be conducted to validate or refute this possibility. Regardless of the quenching mechanism, our data clearly indicate that it is important to control the quantity of atomic oxygen in the flow prior to injecting iodine into the flow.

As discussed in prior works [2]–[5], [7]–[9], [29], it is important to lower the parameter  $E/N$  such that it is close(r) to the optimal excitation cross-section value to attain maximal yields of  $\text{O}_2(a)$ . One way to lower  $E/N$  is to introduce a gas with a lower ionization threshold. NO has an ionization threshold of 9.26 eV, which is significantly lower than the 12.07-eV threshold of  $\text{O}_2$ . Experiments were conducted by adding NO to the flow. It

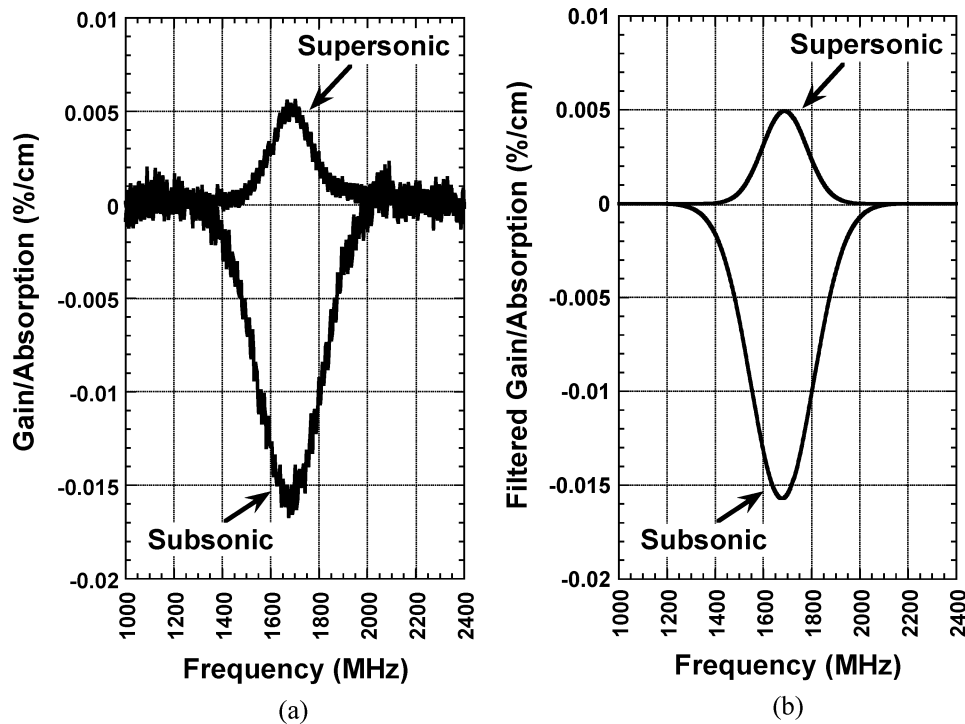


Fig. 14. Gain in the subsonic diagnostic section and the supersonic cavity as a function of frequency at 400-W RF discharge power with cooled  $N_2$  injected upstream of the throat. (a) Raw signal. (b) Digitally filtered signal. Positive gain was observed in the supersonic section and absorption in the subsonic section.

was found that NO additions of approximately 1%–10% of the  $O_2(a)$  flow rate produced the largest increases in the production of  $O_2(a)$  and typically around 4%–5% was optimal. Fig. 10 shows the significant improvement ( $\sim 33\%$ ) attained with a 4% (0.2 mmol/s) addition of NO in a flow of 5 mmol/s of  $O_2$  mixed with 20 mmol/s of He at 10-torr total pressure. We believe that the principle cause of this increase is a drop in  $E/N$ , which shows up as a drop in the measured RF voltage (see Fig. 11), however, there are likely other effects of having NO in the discharge that we do not yet understand. If we assume a constant field from electrode to electrode and a constant current, we would estimate that our  $E/N$  is 12–18 Td whereas the optimal  $E/N$  is approximately 5 Td [26]; therefore, there is still considerable room for improvement. While Fig. 11 does not show a large change in voltage, it does not take a large change in  $E/N$  to make observably large changes in the  $O_2(a)$  production since we are operating in the steep part of the electron energy distribution function curve [8], [26]. While our type of discharge would be classically considered a self-sustained discharge, we appear to be operating in a nonself-sustained fashion because our  $E/N$  of approximately 15 Td is considerably lower than a predicted self-sustained  $E/N$  of approximately 80 Td. The reason for this is not completely understood, but we believe it may have to do with the VUV emission in the hollow cathode part of the discharge causing photo-ionization downstream and hence lowering the  $E/N$  from the classic mode. It is also true that the lower  $E/N$  is a consequence of an average of the nonuniform distribution of  $E_z$  due to capacitive shunting of the RF currents to ground. Thus, the plane of the driven electrode has a much higher  $E/N$ . Obviously this is a case for further study.

Several flow conditions were found that resulted in positive gain using the configuration shown in Fig. 1. A typical set of

conditions is 4 mmol/s of  $O_2$  mixed with 16 mmol/s of He and 0.2 mmol/s of NO flowing through a 400 W RF discharge. An additional 0.2 mmol/s of  $NO_2$  was added downstream to scavenge some of the excess O atoms, followed by injection of a secondary stream of 0.008 mmol/s of  $I_2$  with 2.0 mmol/s of secondary He diluent. To raise the pressure for more ideal nozzle performance with our vacuum system, 20 mmol/s of Ar was injected further downstream. The pressures in the subsonic diagnostic duct and in the supersonic diagnostic cavity were 10.6 and 1.6 torr, respectively.

Absorption in the subsonic region for these conditions was  $-0.009\% \text{ cm}^{-1}$ , with a temperature of 400 K, and an  $O_2(a)$  yield of approximately 15% (as computed from the gain/spectral technique outlined by Rawlins *et al.* [12]). Based on these measurements, positive gain could be expected if the gas temperature could be sufficiently reduced. As such, gain measurements in the supersonic cavity were made for the above flow conditions as shown in Figs. 12 and 13. With 100 W of RF discharge power and a yield of approximately 5%, only absorption was observed. Upon raising the discharge power to 400 W, positive gain of  $\approx 0.002\% \text{ cm}^{-1}$  was measured. The measured line-shapes were digitally filtered [Fig. 12(b)] and then corrected for homogeneous broadening due to He, Ar, and  $O_2$  to obtain the Doppler width according to the procedure outlined by Whiting [27]. From the resulting Doppler width, we obtain a temperature of  $\approx 210$  K at 100 W and  $\approx 240$  K at 400 W in the supersonic region. To the best of our knowledge, these were the first measurements of positive gain in a continuously flowing iodine system with  $O_2(a)$  being provided by an electric discharge [11]. Interestingly, the first measurement of positive gain on a classic liquid chemistry COIL system was also on the order of  $0.001\% \text{ cm}^{-1}$  [28].

By adding precooled ( $\approx 180$  K) Ar upstream of the nozzle throat and raising the upstream pressure to 13 torr, we were able to make further improvements to the gain by lowering the total temperature and increasing the density. Fig. 14 shows both a positive gain trace in the supersonic cavity and the corresponding absorption trace in the subsonic cavity. The flow conditions were the same for this case as discussed above with the exception of raising the Ar flow rate to 38 mmol/s of Ar to raise the upstream total pressure to 13 torr. The gain in the supersonic cavity was measured to be  $\approx 0.005\% \text{ cm}^{-1}$  at 400 W of RF discharge power. From the digitally filtered traces [Fig. 14(b)] and the homogeneous broadening correction, we obtain temperatures of  $\approx 220$  K in the supersonic cavity and  $\approx 375$  K in the subsonic region. We have also obtained similar magnitudes of positive gain using precooled  $\text{N}_2$  upstream of the nozzle throat; for these cases, the temperature of the  $\text{N}_2$  entering the flow tube was  $\approx 150$  K and the flow rate was 50 mmol/s of  $\text{N}_2$  to raise the pressure to 12.5 torr.

#### IV. CONCLUDING REMARKS

Conditions for positive gain were established on the  $\text{I}^* \rightarrow \text{I}$  electronic transition of the iodine atom at 1315 nm pumped by a near-resonant energy transfer from  $\text{O}_2(a)$  produced in an electric RF discharge. A supersonic cavity was employed to lower the temperature of the flow and reduce the effect of the backward pumping reaction. This produced sufficient population inversion to observe a small but easily identifiable positive gain of approximately  $0.005\% \text{ cm}^{-1}$ . The critical issues that needed to be addressed to attain positive gain were improvements to the discharge flow and stability, along with a significantly more complete understanding of the gas-phase kinetics. Atomic oxygen was found to play both a positive role and a deleterious role in this system, and, as such, the excess atomic oxygen was controlled to minimize the deleterious effects. The discharge production of  $\text{O}_2(a)$  was enhanced by the addition of a small proportion (4%–5% of the  $\text{O}_2$  flow rate) of NO to lower the ionization threshold of the gas mixture.

#### APPENDIX A

One can use the fact that the decay of  $\text{O}_2(a)$  and  $\text{I}^*$  are simple exponentials of the flow distance  $z$  to obtain an estimate for the  $\text{I}^* + \text{O}$  quenching reaction rate  $k_4$  as follows:

$$\begin{aligned} \frac{d[\text{I}^*]}{dz} &= \frac{1}{u_f} \cdot \frac{d[\text{I}^*]}{dt} \\ &= \frac{k_1 [\text{O}_2(a)] [\text{I}]}{u_f} - \frac{k_{-1} [\text{O}_2(X)] [\text{I}^*]}{u_f} - \frac{k_4 [\text{O}] [\text{I}^*]}{u_f} \end{aligned} \quad (\text{A1})$$

$$\begin{aligned} \frac{d[\text{O}_2(a)]}{dz} &= \frac{1}{u_f} \cdot \frac{d[\text{O}_2(a)]}{dt} \\ &= -\frac{k_1 [\text{O}_2(a)] [\text{I}]}{u_f} + \frac{k_{-1} [\text{O}_2(X)] [\text{I}^*]}{u_f}. \end{aligned} \quad (\text{A2})$$

By adding (A1) and (A2), recognizing that the first two terms of the right-hand side of each equation cancel exactly, and using the fact that  $[\text{O}_2(a)] \gg [\text{I}^*]$ , one can obtain

$$\frac{d\{[\text{O}_2(a)] + [\text{I}^*]\}}{dz} \cong \frac{d[\text{O}_2(a)]}{dz} = -\frac{k_4 [\text{O}] [\text{I}^*]}{u_f}. \quad (\text{A3})$$

Both  $[\text{O}_2(a)]$  and  $[\text{I}^*]$  decay exponentially (Fig. 8) with approximately the same spatial rate; hence, the concentrations take the functional form of  $[\text{O}_2(a)](z) = [\text{O}_2(a)]_0 \exp(-z/L)$  and  $[\text{I}^*](z) = [\text{I}^*]_0 \exp(-z/L)$ , where  $L$  is the characteristic exponential decay length, and (A3) can be written as

$$\begin{aligned} \frac{d[\text{O}_2(a)]}{dz} &= -\frac{1}{L} [\text{O}_2(a)]_0 \exp\left(-\frac{z}{L}\right) \\ &= -\frac{k_4 [\text{O}] [\text{I}^*]_0 \exp\left(-\frac{z}{L}\right)}{u_f}. \end{aligned} \quad (\text{A4})$$

Solving for  $k_4$  gives

$$k_4 = \frac{[\text{O}_2(a)]_0}{[\text{O}]_0 [\text{I}^*]_0} \cdot \frac{u_f}{L}. \quad (\text{A5})$$

#### ACKNOWLEDGMENT

The authors would like to acknowledge the contributions of T. Madden and G. Hager (Air Force Research Laboratory), M. Kushner (Univ. of Illinois), S. Davis, T. Rawlins, and B. Kessler (PSI, Inc.), M. Heaven and K. Morokuma (Emory University), G. Perram (Air Force Institute of Technology), M. Berman (Air Force Office of Scientific Research), B. Otey (U.S. Army Space and Missile Defense Command), A. Ionin (P.N. Lebedev Physics Institute), A. Napartovich (Troitsk Institute for Innovation and Fusion Research), and T. Rakhimova (Lomonosov Moscow State University). They would also like to thank T. Field for his technical assistance.

#### REFERENCES

- [1] W. McDermott, N. Pchelkin, D. Benard, and R. Bousek, *Appl. Phys. Lett.*, vol. 32, no. 8, pp. 469–470, 1978.
- [2] R. Zaleskii and V. Yu, *Zh. Eksp. Teor. Fiz.*, vol. 67, pp. 30–37, 1974.
- [3] G. Fournier, J. Bonnet, and D. Pigache, *J. Physique*, vol. 41, p. 449, 1980.
- [4] D. L. Carroll, J. T. Verdeyen, D. M. King, B. S. Woodard, L. W. Skorski, J. W. Zimmerman, and W. C. Solomon, *IEEE J. Quantum Electron.*, vol. 39, no. 9, pp. 1150–1159, Sep. 2003.
- [5] D. L. Carroll, J. T. Verdeyen, D. M. King, B. S. Woodard, J. W. Zimmerman, L. W. Skorski, and W. C. Solomon, “Recent experimental measurements of the ElectricOIL system,” in *Proc. AIAA*, 2003, paper 2003-4029.
- [6] J. Schmiedberger, S. Hirahara, Y. Ichinoche, M. Suzuki, W. Masuda, Y. Kihara, E. Yoshitani, and H. Fujii, *SPIE*, vol. 4184, pp. 32–35, 2001.
- [7] *2000 Proc. Int. Conf. Lasers*, V. Corcoran and T. Corcoran, Eds., McClean, VA, 2001, pp. 249–258.
- [8] A. A. Ionin, Y. M. Klimachev, A. A. Kotkov, I. V. Kochetov, A. P. Napartovich, L. V. Seleznev, D. V. Sinitsyn, and G. D. Hager, *J. Phys. D: Appl. Phys.*, vol. 36, pp. 982–989, 2003.
- [9] T. V. Rakhimova, A. S. Kovalev, A. T. Rakhimov, K. S. Klopovsky, D. V. Lopaev, Y. A. Mankelevich, O. V. Proshina, O. V. Braginsky, and A. N. Vasilieva, “Radio-frequency plasma generation of singlet ( $a^1\Delta_g$ ) oxygen in  $\text{O}_2$  and  $\text{O}_2 : \text{Ar}$  (He) mixtures,” in *Proc. AIAA*, 2003, paper 2003-4306.
- [10] D. S. Stafford and M. J. Kushner, “ $\text{O}_2(^1\Delta)$  production in He/ $\text{O}_2$  mixtures in flowing low pressure plasmas,” *J. Appl. Phys.*, vol. 96, no. 5, pp. 2451–2465, 2004.

- [11] D. L. Carroll, J. T. Verdeyen, D. M. King, J. W. Zimmerman, J. K. Laystrom, B. S. Woodard, N. Richardson, K. Kittell, M. J. Kushner, and W. C. Solomon, "Measurement of positive gain on the 1315 nm transition of atomic iodine pumped by  $O_2(a^1\Delta)$  produced in an electric discharge," *Appl. Phys. Lett.*, vol. 85, no. 8, pp. 1320–1322, 2004.
- [12] W. T. Rawlins, S. J. Davis, S. Lee, M. L. Silva, W. J. Kessler, and L. G. Piper, "Optical diagnostics and kinetics of discharge-initiated oxygen-iodine energy transfer," in *Proc. AIAA*, 2003, paper 2003-4032.
- [13] S. J. Davis, M. G. Allen, W. J. Kessler, K. R. McManus, M. F. Miller, and P. A. Mulhall, *Proc. SPIE-Int. Soc. Opt. Eng.*, vol. 2702, pp. 195–201, 1996.
- [14] G. D. Hager, private communication, Oct. 25, 2002.
- [15] R. G. Derwent and B. A. Thrush, *Discuss. Faraday Soc.*, vol. 53, pp. 162–167, 1972.
- [16] G. P. Perram and G. D. Hager, "The Standard COIL Kinetics Package," Air Force Weapons Laboratory, Kirtland Air Force Base, Final Rep. AFWL-TR-88-50, 1988.
- [17] J. Hon, G. Hager, C. Helms, and K. Truesdell, *AIAA J.*, vol. 34, no. 8, pp. 1595–1603, 1996.
- [18] W. A. Payne, R. P. Thorn Jr., F. L. Nesbitt, and L. J. Stief, *J. Phys. Chem. A*, vol. 102, pp. 6247–6250, 1998.
- [19] M. C. Heaven, private communication, Oct. 4, 2001.
- [20] J. Han, S. P. Tinney, and M. C. Heaven, "I\* kinetics of relevance to discharge driven COIL systems," in *Proc. SPIE-Int. Soc. Opt. Eng.*, vol. 5448, 2004, pp. 261–268.
- [21] F. Kaufman, *Proc. Roy. Soc. A*, vol. 247, pp. 123–139, 1958.
- [22] R. Atkinson, D. L. Baulch, R. A. Cox, R. F. Hampson Jr., J. A. Kerr, M. J. Rossi, and J. Troe, "Evaluated kinetic, photochemical and heterogeneous data for atmospheric chemistry: supplement V," *J. Phys. Chem. Ref. Data*, vol. 26, no. 3, pp. 550–962, 1997.
- [23] R. F. Heidner III, C. E. Gardner, T. M. El-Sayed, G. I. Segal, and J. V. V. Kasper, "Temperature dependence of  $O_2(a^1\Delta) + O_2(a^1\Delta)$  and  $I(^2P_{1/2}) + O_2(a^1\Delta)$  energy pooling," *J. Chem. Phys.*, vol. 74, no. 10, pp. 5618–5626, 1981.
- [24] L. Sentman, M. Subbiah, and S. Zelazny, "Blaze II: A Chemical Laser Simulation Computer Program," Bell Aerospace Textron, Buffalo, NY, Tech. Rep. H-CR-77-8, 1977.
- [25] M. C. Heaven, private communication, Apr. 23, 2004.
- [26] D. L. Carroll, J. T. Verdeyen, J. W. Zimmerman, L. W. Skorski, and W. C. Solomon, "Recent electrodynamic modeling of the ElectricCOIL system," in *Proc. AIAA*, 2003, paper 2003-4030.
- [27] E. E. Whiting, "An empirical approximation to the voigt profile," *J. Quantum Spectrosc. Radiat. Transfer.*, vol. 8, pp. 1379–1384, 1968.
- [28] A. T. Pritt Jr., R. D. Coombe, D. Pilipovich, R. I. Wagner, D. Benard, and C. Dymek, *Appl. Phys. Lett.*, vol. 31, pp. 745–747, 1977.
- [29] V. Yu. Zalesskii, *Sov. Phys. JETP*, vol. 40, no. 1, pp. 14–17, 1975.

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