

Enhancement of electric oxygen-iodine laser performance using larger mode volume resonators

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Herein the authors report on the demonstration of an 87% enhancement in cw laser power on the 1315 nm transition of atomic iodine via a 100% increase in the resonator mode volume. $O_2(a^1\Delta)$ is produced by a single rf-excited electric discharge sustained in an O_2 -He-NO gas mixture flowing through a rectangular geometry, and $I(^2P_{1/2})$ is then pumped using energy transferred from $O_2(a^1\Delta)$. A total laser output power of 102.5 W was obtained using a Z-pass resonator configuration. © 2010 Optical Society of America
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The electrically driven oxygen-iodine laser (ElectricOIL) that was first demonstrated by Carroll *et al.* [1], 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 $O_2(a)$]. Since the first demonstration there has been a steady and systematic progress in increasing the ElectricOIL gain and lasing [2–5] in various configurations. Ionin *et al.* [6] and Heaven [7] provided comprehensive topical reviews of the discharge production of $O_2(a)$ and ElectricOIL studies by various groups.

In this Letter we report on the recent demonstration of an 87% enhancement in the cw laser power on the 1315 nm transition of atomic iodine via a 100% increase in the resonator mode volume. There are unidentified kinetic processes that are occurring in the ElectricOIL system [8,9]. Measurements of the gain recovery downstream of an operating laser cavity were performed by Zimmerman *et al.* [9] and suggest that the unidentified kinetics include a competing effect with the pumping reaction. Modeling of these experiments showed that reducing the forward pumping rate by an effective factor of approximately 4 to simulate a competing mechanism results in the computational modeling matching the experimental gain recovery measurements, and in an improved agreement between the measured and modeled laser power extractions. Note that Zimmerman *et al.* [9] are not suggesting that the established forward pumping rate is in error, only that there is an additional competing process that is occurring in the ElectricOIL system kinetics due to additional species not present in the classic chemical oxygen-iodine laser. As a result of these experimental measurements it was hypothesized that a larger volume resonator that extends further downstream in the flow direction would be able to extract more of the excess energy being carried by $O_2(a)$ from the ElectricOIL gain medium [9]. In this Letter, we present experiments that focus on validating this hypothesis and show

that there are corresponding system design methods that can successfully address this slower than anticipated gain recovery (energy transfer) issue.

In an effort to understand the resonator mode volume size effects on the ElectricOIL performance we studied three different resonator configurations [Figs. 1(a)–1(c)]: (i) a simple stable resonator with 2 in. diameter mirrors (as tested in prior work [5]), (ii) a simple stable resonator with 4 in. diameter mirrors (rather than 2 in. diameter mirrors), and (iii) a Z-pass resonator design. The basic experimental layout is illustrated in Figs. 1(a)–1(c). $O_2(a)$ is produced by a transverse capacitive 13.56 MHz rf-excited electric discharge sustained in an O_2 -He (plus a trace of NO) gas mixture, the ground state $I(^2P_{3/2})$ is produced by the dissociation of I_2 when reacting with O atoms created in the discharge, and $I(^2P_{1/2})$ is then produced using energy transferred from $O_2(a)$. The supersonic laser cavity has a Mach 2 nozzle with purged optical mounts into which can be placed either wedged windows for the measurement of the gain or high-reflectivity mirrors for laser oscillation. This work builds upon prior experiments, the sixth generation laser cavity (“Cav6”) hardware, and diagnostics detailed in [5]. The gain length of the Cav6 laser cavity is 7.6 cm. For brevity, with the exception of the resonator configurations tested in this work, many of the details of the experimental configuration are not discussed herein and can be found in [5].

The single rectangular cross-section transverse discharge (having an electrode gap of 2.2 cm) from [5] was implemented for experiments with the 4 in. diameter mirrors. Owing to fracturing that occurred in this quartz rectangular tube after considerable use, a six-tube configuration using 1.9 cm outside diameter quartz discharge tubes was utilized (not shown for brevity) for the Z-pass resonator experiments, which occurred after the 4 in. diameter mirror testing. The rectangular quartz tube was not replaced for cost and time constraint reasons. The six-tube configuration required the use of two discharges (one upstream and one downstream) with the upstream discharge necessary to initiate discharge uniformity in all of the

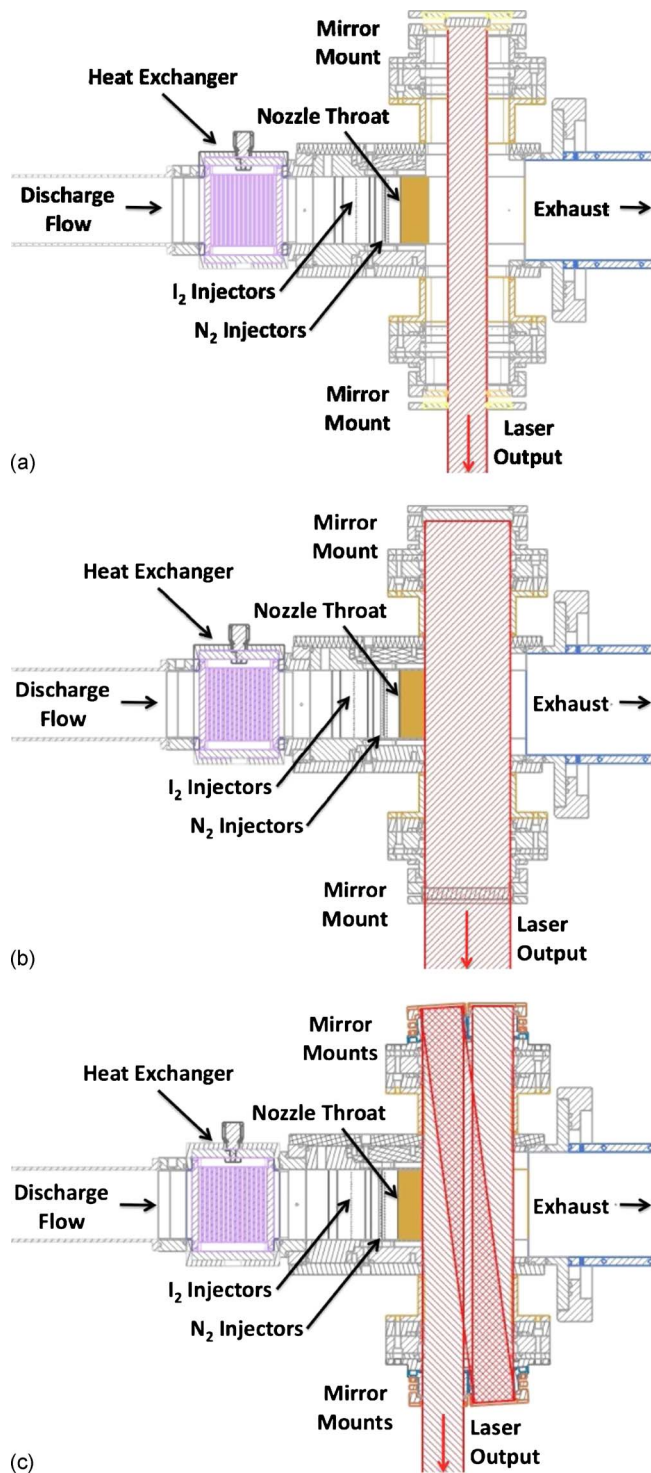


Fig. 1. (Color online) Different resonator configurations tested with the Cav6 hardware: (a) stable resonator with 2 in. diameter optics, (b) stable resonator with 4 in. diameter optics, and (c) Z-pass stable resonator with four 2 in. diameter optics. (Note: the Z-pass configuration was tested with a six-tube discharge rather than a rectangular discharge.)

tubes. Flow rates and pressures were approximately the same as those used in the rectangular tube; however, total discharge powers were typically 15%–35% higher (depending on operating conditions) with the six-tube configuration to obtain the same laser output power with 4 in. diameter optics. This strongly

indicates that the rectangular discharge tube configuration is desirable in terms of the electrical efficiency of the system.

Laser power measurements were made with Scientech Astral model UC150HD40 and AC5000 calorimeters interfaced to a pair of Scientech Vector model S310 readouts. Only one pair of 4 in. diameter mirrors was tested because of the expense, a pair of 0.9970 reflective mirrors from AT Films; one mirror had 2 m radius of curvature and the other was a flat mirror. When using the 4 in. diameter mirrors the outcoupled beam was transmitted through 4 in. diameter lenses to reduce the beam size such that the entire beam would fit inside the aperture of the Scientech power meters. For the Z-pass configuration, several different sets of mirrors purchased from AT Films, Los Gatos Research, and CVI were put in place for the laser power trials. The lowest reflectivity mirror used had a reflectivity of 0.9648 and the highest had a reflectivity of 0.999 95. The product of the four mirror reflectivities ranged from 0.9618 to 0.9968. The mirrors used were typically a mixture of 2 m radius of curvature and flat mirrors, and formed a stable optical cavity. For the mirror configurations shown in Figs. 1(a) and 1(b), the mirrors were separated by 41.9 cm and were located with an optical axis 7.4 cm downstream from the throat of the nozzle. For the mirror configuration shown in Fig. 1(c), the first and last mirrors in the Z-pass resonator were separated by a total path length of approximately 129.0 cm. An IR detection card from New Focus, Model 5842, with a 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 are 44 mmol/s of O_2 , which is diluted with 150 mmol/s of He and 0.23 mmol/s of NO. A secondary stream of ≈ 0.30 mmol/s of I_2 with 46 mmol/s of secondary He diluent was injected 26.7 cm downstream from the exit of the primary discharge. A tertiary flow of 312 mmol/s of cold N_2 gas (≈ 100 K) was injected further downstream to lower the temperature, improve mixing, and improve the performance of the nozzle in our vacuum system. The pressures in the discharge region and in the supersonic diagnostic cavity were 45.0 and 4.0 Torr, respectively.

Gain measurements were made prior to all lasing tests to ensure that the experimental hardware and flow conditions were providing the expected gain. For all laser power measurements presented herein the gain at the line center peaked at $0.25\%–0.26\% \text{ cm}^{-1}$, which is consistent with [5]. The gain was the same regardless of the discharge configuration tested (rectangular or six-tube), but as discussed above more discharge power was required for the six-tube configuration.

Figure 2 compares the data from the three different mirror configurations [Figs. 1(a)–1(c)] as a function of the product of the mirror reflectivities [$r_1 r_2$ for the configurations shown in Figs. 1(a) and 1(b), and $r_1 r_2 r_3 r_4$ for the Z configuration shown in Fig. 1(c)]. Rigrod curves modified to include diffractive loss effects [10] are also plotted. The 4 in. diameter mirrors

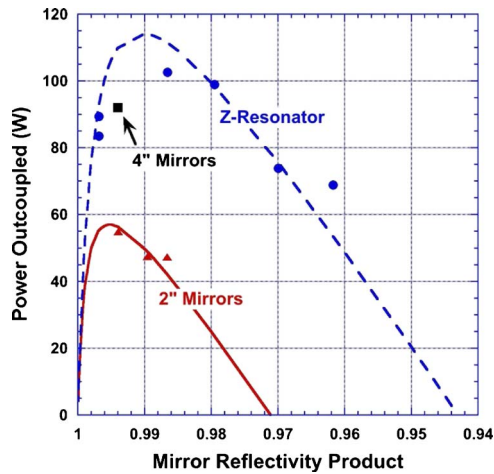


Fig. 2. (Color online) Outcoupled power versus mirror reflectivity product as a function of resonator configuration (Fig. 1) with Cav6 hardware. Curves generated from Rigrod theory with a diffraction loss term [10] are illustrated for comparison to data for the 2 in. and Z-pass resonator configurations.

produced an output power of 92.0 W with an input rf power of 3750 W using a rectangular discharge and a mirror reflectivity product of 0.9940. The Z-resonator peak power was 102.5 W with an input rf power of 5000 W using a six-tube discharge configuration and a mirror reflectivity product of 0.9865. Thus, by using a larger mode volume resonator we increased the output power by 87% (54.8 W with 2 in. mirrors increased to 102.5 W with the Z-pass configuration) thereby demonstrating that: (i) there is a considerable amount of extractable power still available in the ElectricOIL flow and (ii) that there are ways to extract this power as useful laser energy.

In conclusion, the authors observed an 87% increase in the outcoupled power and efficiency through the use of a larger (approximately a factor of 2) mode volume resonator. An output power of 92.0 W was obtained with two 4 in. diameter 0.9970 reflective mirrors, and an output power of 102.5 W was obtained with a Z-pass configuration using a combination of four 2 in. diameter mirrors having reflectivities of 0.9896, 0.9970, 0.999 95, and 0.999 95. A continued expansion of the operating envelope to higher flow conditions, pressures, and gain lengths of the laser cavity, plus the addition of an iodine pre-dissociator [11], is expected to provide significant increases to the gain and laser power. The re-

sults presented herein represent more than 2 orders of magnitude improvement in gain and laser power since the initial demonstration in 2005 [1].

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