APPLIED PHYSICS LETTERS **95**, 221112 (2009)

Enhancement of electric oxygen-iodine laser performance using a rectangular discharge and longer gain length

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(Received 7 October 2009; accepted 8 November 2009; published online 3 December 2009)

Herein the authors report on the demonstration of a 95% enhancement in continuous-wave laser power on the 1315 nm transition of atomic iodine via a 50% increase in gain length, flow rates, and discharge power. $O_2(a\ ^1\Delta)$ is produced by a single radio-frequency-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 gain of 0.26% cm^{-1} was obtained and the total laser output power was 54.8 W. © *2009 American Institute of Physics*. [doi:10.1063/1.3269811]

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 steady and systematic progress in increasing ElectricOIL gain and lasing[2–4] in various configurations. Ionin *et al.*[5] provide a comprehensive topical review of discharge production of $O_2(a)$ and ElectricOIL studies by various groups.

In this letter the authors report on the demonstration of a 95% enhancement in continuous-wave laser power on the 1315 nm transition of atomic iodine via a 50% increase in gain length, flow rates, and discharge power. The increase in gain length (and correspondingly the flow rates) was motivated by the desire for more understanding of the system. Recent theoretical investigations have indicated that the combination of short gain length (5.1 cm) with gain $<0.25\%\ cm^{-1}$ (which requires highly reflective mirrors for lasing) results in significant diffractive losses inside the laser hardware that thereby reduce the extracted power from the gain medium.[6] To help alleviate this problem we increased the 5.1 cm gain length of the prior fifth generation "Cav5" laser cavity[2] to 7.6 cm in the new sixth generation "Cav6" laser cavity discussed herein. Longer gain length enables lower reflectivity mirrors to be used for the resonator, which reduces the number of passes a photon makes within the resonator, and thereby lowers the amount of energy lost to diffractive spill (or equivalently increases the fraction of power extracted from the gain medium). Longer gain lengths than 7.6 cm were considered for design and fabrication, but cost and possible vacuum pumping limitations led us to choose 7.6 cm as a gain length that would give significant support to the above proposition.

$O_2(a)$ is produced by a single transverse capacitive 13.56 MHz rf excited electric discharge sustained in an $O_2-He-NO$ gas mixture flowing through a rectangular cross-section channel, and $I(^2P_{1/2})$ is then pumped using energy transferred from $O_2(a)$; the electrode gap (1.6 cm) in the primary discharge is transverse to the flow direction. A block diagram of the flow tube setup is shown in Fig. 1. The quartz rectangular discharge channel section has an internal flow cross section of 1.6 cm by 7.5 cm. The plasma zone filled the transverse gap of 1.6 cm and was 50.8 cm long (the gap between the parallel plate electrodes, the outside dimension of the flow channel, was 2.2 cm, i.e., the quartz tube walls were 0.3 cm thick). In prior experiments, single and multiple 1.6 cm internal diameter discharge tubes were utilized that resulted in substantially increased discharge stability at higher pressure while maintaining significant $O_2(a)$ yields. More information related to 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 Woodard *et al.*[7] and Zimmerman *et al.*[2] The disadvantage to these smaller tubes is that they limited the amount of gas flow that could be run through them without creating substantial pressure rises in the discharge tubes [detrimental to the resulting $O_2(a)$ yields]. As such, it was felt that switching to a high aspect ratio rectangular discharge channel would enable us to simultaneously maintain the good discharge characteristics with a small discharge gap while at the same time permitting higher flow rates without any increase in discharge pressure. A water cooled heat exchanger was located at the exit of the discharge channel to cool the discharge gases before entering the laser cavity section.

The supersonic diagnostic cavity has a Mach 2 nozzle with purged optical mounts into which can be placed either

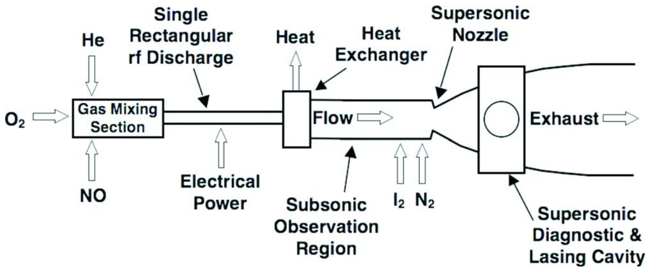

FIG. 1. (Color online) Block diagram of the experimental apparatus.

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wedged windows for measurement of the gain or high-reflectivity mirrors for laser oscillation. The gain length of the Cav6 laser cavity is 7.6 cm. Supersonic bank blowers, flowing in the same direction as the gain medium gases, were added to the Cav6 design at the sides of the gain medium to provide better gas flow confinement. The bank blowers eliminate recirculation regions that could absorb photons and prevent contamination of the laser mirrors.

Micro-Motion CMF and Omega FMA mass flow meters were used to measure the flow rates of the gases, including the gaseous I_2. Pressure in the subsonic and supersonic flow regions were measured by capacitance manometers from MKS and Leybold.

Prior to gain and laser experiments, flow tube measurements of the optical emission from $O_2(a)$ at 1268 nm and $O_2(b\ {}^1\Sigma)$ [denoted hereafter as $O_2(b)$] at 762 nm were made downstream from the exit of the rectangular discharge in a purged subsonic observation region. A Roper scientific optical multichannel analyzer 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 $O_2(b)$ transition about 762 nm. Both instruments are fiber-coupled to enable instrument positioning flexibility and excellent measurement repeatability. These measurements indicated an $O_2(a)$ yield of ≈12.5% and a gas temperature of ≈625 K for these flow conditions at 4000 W of rf power. The temperature of the gas flow drops to ≈450 K after flowing through the water cooled heat exchanger with less than one yield percent loss in the $O_2(a)$ (similar to results from Ref. 2).

Measurements of gain (or absorption) were made prior to operating the system as a laser using the Iodine-Scan Diagnostic (ISD) developed by Physical Sciences Inc. (PSI).[8] Since the ISD uses a narrow band diode laser, measurements of the line shapes 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 (7.6 cm path length) was used in the supersonic diagnostic section.

Laser power measurements were made with Scientech Astral™ model AC5000 and UC150HD40 calorimeters interfaced to a pair of Scientech Vector™ model S310 readouts. Different sets of mirrors purchased from AT Films were then put in place for the laser power trials. The lowest reflectivity set of mirrors used was a 0.9896 and 0.9970 combination, the middle reflectivity set was a 0.9896 and 0.999 97 combination, and the highest reflectivity combination was a pair of 0.9970 mirrors. All of the mirrors used had a 2 m radius of curvature and the pair formed a stable optical cavity. The mirrors were separated by approximately 41.9 cm and were located with an optical axis 7.4 cm downstream from the throat of the nozzle. An infrared detection card from New Focus, Model 5842, with response between 800–1600 nm, was also used to observe the intensity profile of the beam. The beam profile was also captured by burning black polycarbonate plates.

The flow conditions for these gain and laser power experiments with the single rectangular primary discharge 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.

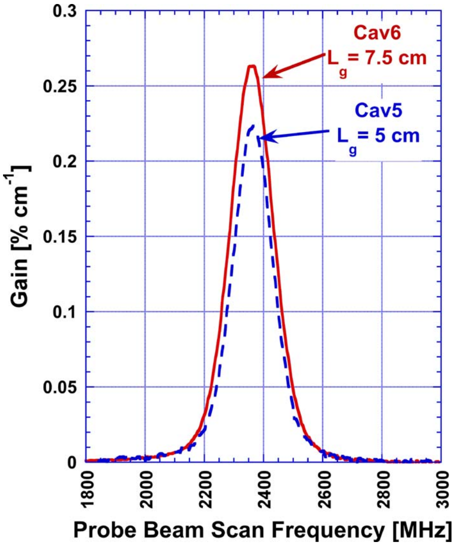

FIG. 2. (Color online) Gain line shapes in the supersonic cavity as a function of probe beam scan frequency for the 5.1 cm gain length Cav5 (from Ref. 2) and the 7.6 cm Cav6 hardware (this work).

Gain was measured for the above flow conditions at a total of 4000 W of primary rf discharge power. Figure 2 shows the gain at line center which peaks at 0.26% cm^{-1} with the rectangular primary discharge. For comparison, the best gain previously observed[2] in our system was 0.22% cm^{-1}, using four 1.9 cm outside diameter (1.6 cm inside diameter) primary discharge tubes and roughly two-thirds of the flow rates at 53 Torr total pressure (4.7 Torr in the supersonic diagnostic cavity). Since we kept the discharge flow conditions and discharge power per O_2 molecule approximately the same, we did not anticipate any major changes in gain for these Cav6 experiments as compared to the Cav5 experiments. However, we did see an 18% enhancement in gain, most likely due to improvements in flow uniformity with the rectangular discharge and better flow confinement in the laser cavity when using the supersonic bank blowers. The line shapes indicate temperatures of ≈125 K in the laser cavity.

The Cav6 supersonic gain medium was used as the active medium for the stable resonator. For the above 45 Torr flow conditions, total laser output powers of 47.8, 47.3, and 54.8 W were obtained for the three aforementioned mirror sets in order of increasing product of reflectivity, respectively, Fig. 3. Note that the 54.8 W result is a 98% improvement to laser power relative to the 28.1 W result from Ref. 2 for only a 50% increase in gain length, flow rates, and discharge input power. The beam shape was rectangular with rounded corners and had a length of ≈4.45 cm in the flow direction and a height of ≈2.5 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).

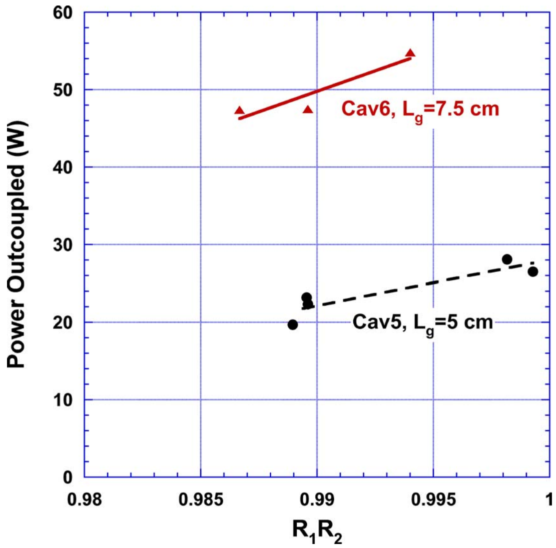

FIG. 3. (Color online) Outcoupled laser power data as a function of the product of the mirror reflectivities for the 5.1 cm gain length Cav5 (from Ref. 2) and the 6 cm Cav6 hardware (this work).

In conclusion, the authors observed a 95% enhancement in continuous-wave laser power on the 1315 nm transition of atomic iodine through the use of a longer gain length laser cavity and a rectangular discharge for only a 50% increase in gain length, flow rates, and discharge input power. A gain of 0.26% cm^{-1} was obtained and the laser output power was 54.8 W in a stable cavity with two 0.9970 reflective mirrors. The implementation of a longer gain length cavity permits us to use lower reflectivity resonator mirrors that reduce diffractive spill losses, and thereby more efficiently extract power from the gain medium. A continued expansion of the operating envelope to higher flow conditions, pressures, and gain length of the laser cavity, plus the addition of an iodine predissociator[9] are expected to provide significant increases to the gain and laser power. The results presented herein represent more than two orders of magnitude improvement in gain and laser power since the initial demonstration in 2005.[1]

This work was supported by DARPA prime Contract No. HR0011-07-C-0054 on a subcontract from Physical Sciences Inc. (PSI). Additionally, J. Zimmerman was supported in part by the Directed Energy Professional Society (DEPS) Scholarship Program. The authors gratefully acknowledge the contributions of W.T. Rawlins, S.J. Davis, and S. Lee (PSI); M. Heaven (Emory University); and G.W. Sutton (SPARTA/Cobham Analytic Solutions). The views, opinions, and/or findings contained in this letter are those of the authors and should not be interpreted as representing the official views or policies, either expressed or implied, of the Defense Advanced Research Projects Agency or the Department of Defense. Distribution Statement A (approved for public release, distribution unlimited).

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