PLASMA EXCITED CHEMICAL-OXYGEN-IODINE LASERS: OPTIMIZING INJECTION AND MIXING FOR POSITIVE GAIN*

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60th Annual Gaseous Electronics Conference
October 4
2007

* Work supported by Air Force Office of Scientific Research and National Science Foundation.
AGENDA

• Introduction to eCOIL
• Oxygen-iodine kinetics mechanism
• Description of model
• Gain and flow properties for I₂ injection strategies.
• Concluding Remarks
ELECTRICALLY EXCITED OXYGEN-IODINE LASERS

- In chemical oxygen-iodine lasers (COILs), oscillation at 1.315 μm $I^{(2P_{1/2})} \rightarrow I^{(2P_{3/2})}$ occurs by excitation transfer of $O_2(^1\Delta)$ to $I_2$ and I.

- Plasma production of $O_2(^1\Delta)$ in electrical COILs (eCOILs) eliminates liquid phase generators.

- $I_2$ injection and supersonic expansion (to lower $T_{gas}$ for inversion) occurs downstream of the plasma zone.

Ref: CU Aerospace

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O$_2$($^{1}\Delta$) KINETICS IN He/O$_2$ DISCHARGES

- Direct electron impact of excitation of O$_2$ to O$_2$($^{1}\Delta$) and O$_2$($^{1}\Sigma$) are main channels of O$_2$($^{1}\Delta$) production.
- Dissociation of O$_2$ limits O$_2$($^{1}\Delta$) production while O and O$_3$ are the main quenchers of O$_2$($^{1}\Delta$).

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O₂-I₂ KINETICS

• In conventional COILs, dissociation of I₂ is by excitation transfer from O₂(¹Δ, ¹Σ).

\[
I₂ + O₂(¹Δ) → I₂^* + O₂ \\
I₂^* + O₂(¹Δ) → I(²P_{3/2}) + I + O₂ \\
I₂ + O₂(¹Σ) → I(²P_{3/2}) + I + O₂
\]

• Excitation transfer from O₂(¹Δ) pumps the upper laser level.

\[
I(²P_{3/2}) + O₂(¹Δ) → I(²P_{1/2}) + O₂
\]

• In eCOIL, O atoms additionally dissociate I₂ and quench I(²P₁/₂).

\[
I₂ + O → IO + I(²P_{3/2}) \\
I(²P_{1/2}) + O → O + I(²P_{3/2})
\]

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METHOD OF I$_2$ INJECTION

- In eCOILs, the strategy for I$_2$ injection is important to maximizing gain.

- Unlike conventional COIL, O$_2$(^1$\Delta$), O$_2$(^1$\Sigma$) and O are in the flow where I$_2$ is injected, thereby complicating the kinetics.

- In this talk, results from a computational investigation of I$_2$ injection in eCOILs will be discussed with the goal of maximizing gain.

- Ref: CU Aerospace

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DESCRIPTION OF 2d-nonPDPSIM: CHARGED PARTICLES, SOURCES

- Poisson’s equation, continuity equations and surface charge are simultaneously solved using a Newton iteration technique.

\[- \nabla \cdot \varepsilon \nabla \Phi = \sum_j N_j q_j + \rho_s\]

\[\frac{\partial N_j}{\partial t} = -\nabla \cdot \tilde{\phi}_j + S_j\]

\[\frac{\partial \rho_s}{\partial t} = \sum_j -q_j (\nabla \cdot \tilde{\phi}_j + S_j) - \nabla \cdot (\sigma (-\nabla \Phi))\]

- Electron energy equation:

\[\frac{\partial (n_e \varepsilon)}{\partial t} = \tilde{j} \cdot \tilde{E} - n_e \sum_i \Delta \varepsilon_i N_i \kappa_i - \nabla \cdot \left( \frac{5}{2} \varepsilon \Phi - \lambda \nabla T_e \right), \quad \tilde{j} = q \tilde{\phi}_e\]
DESCRIPTION OF 2d-nonPDPSIM: NEUTRAL PARTICLE TRANSPORT

• Fluid averaged values of mass density, mass momentum and thermal energy density obtained using unsteady algorithms.

\[
\frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \vec{v}) + (\text{inlets, pumps})
\]

\[
\frac{\partial (\rho \vec{v})}{\partial t} = \nabla(NkT) - \nabla \cdot (\rho \vec{v} \vec{v}) - \nabla \cdot \mu + \sum_i q_i N_i \vec{E}_i
\]

\[
\frac{\partial (\rho c_p T)}{\partial t} = -\nabla\left(-\kappa \nabla T + \rho \vec{v} c_p T \right) + P_i \nabla \cdot \nu_f - \sum_i R_i \Delta H_i + \sum_i \vec{j}_i \cdot \vec{E}
\]

• Individual fluid species diffuse in the bulk fluid.

\[
N_i(t + \Delta t) = N_i(t) - \nabla \cdot \left( -D_i N_T \nabla \left( \frac{N_i(t + \Delta t)}{N_T} \right) \right) + S_v + S_s
\]
GEOMETRY AND CONDITIONS

- Cylindrical flow tube 6 cm diameter
- Capacitive excitation (25 MHz) using ring electrodes.
- He/O₂=70/30, 3 Torr, 40 W, 6 lpm (980 cm/s, 60 ms residence time)
- NO₂ injection to control O atom inventory.
- “Cold” equivalent reaction rates for forward and backward reactions:
  \[ I\left(\frac{2}{3}P_{3/2}\right) + O_2\left(^1\Delta\right) \leftrightarrow I\left(\frac{2}{1}P_{1/2}\right) + O_2 \]
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**TYPICAL PLASMA PARAMETERS**

- $[e] = 1.2 \times 10^{10} \text{ cm}^{-3}$, $T_e = 2.9 \text{ eV}$
- O and $O_2(^1\Delta)$ reach 1-2 $\times 10^{15} \text{ cm}^{-3}$ by electron impact.
- NO$_2$ injection throttles O density.

<table>
<thead>
<tr>
<th>Power</th>
<th>$T_e$</th>
<th>$[e]$</th>
<th>O$_3$</th>
<th>O</th>
<th>O$_2(^1\Delta)$</th>
<th>NO$_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>40 W</td>
<td>2.9 eV</td>
<td>$1.2 \times 10^{10}$</td>
<td>$2.3 \times 10^{13}$</td>
<td>$2 \times 10^{15}$</td>
<td>$1.4 \times 10^{13}$</td>
<td>$9.7 \times 10^{13}$</td>
</tr>
</tbody>
</table>

**He/O$_2$=70/30, 3 Torr, 40 W, 6 lpm: Injection:**
He/I$_2$=99.5/0.5, 36 sccm

**Spiral I$_2$ Injector**
• $I_2$, injected through spiral coil on axis, is completely dissociated by reactions with O and $O_2(^1\Delta)$.

• $I$ and $I^*$ peak near inlets.

• Two high temperature zones: Joule and Frank-Condon heating in discharge zone; and exothermic reactions from NO$_2$ injection.

• He/O$_2$=70/30, 3 Torr, 40 W, 6 lpm: Injection: He/I$_2$=99.5/0.5, 36 sccm
• $\text{O}_2(1\Delta)$ is depleted in pumping reaction. $\text{O}$ totally dissociates $\text{I}_2$.
• $\text{I}^*$ maximum at injector due to $\text{O}$ quenching and $\text{O}_2(1\Delta)$ depletion.
• Small gain in a narrow layer upstream. Low utilization of $\text{O}_2(1\Delta)$
• Same rate of I$_2$ injection into center of O$_2$(^1Δ) flow increases local gain but reduces overall utilization of O$_2$(^1Δ). Note gain upstream.
• More distributed injection of $I_2$ better utilizes $O_2(^1\Delta)$ producing broader region of gain. Note $I_2$ recombination on walls.
Spiral injector provides better match between flow of I$_2$ and incoming flux of O$_2$(^1Δ); and better radial uniformity of gain.
• Wall injection results in small gain due to slow mixing and low utilization of $O_2(^1\Delta)$.

• Moderately high but narrow gain with one injector on axis.

• Optimum utilization with ring and spiral injectors.
Exothermicity of dissociation reactions heats gas.

Spacing of nozzles determines utilization of $O_2(^1\Delta)$. 

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CONCLUDING REMARKS

- Oxygen-iodine kinetics in flowing afterglows for electrically excited chemical-oxygen-iodine lasers has been computationally investigated.

- Gain was optimized using different injection strategies:
  - Wall injection: small and uniform radial gain.
  - One spherical injector: high but narrow radial gain.
  - Ring and spiral injectors can optimize gain: high and uniform gain due to complete O$_2$(^1\Delta)/I$_2$ mixing.
  - Increasing radius of ring/spiral injectors results in more uniform gain along tube radius due to better O$_2$(^1\Delta) utilization.