Hyperspectral Infrared Imaging of HF (v,J) Chemiluminescence and Gain in Chemically Reacting Flowfields

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Hyperspectral Imaging for HF Lasers

- HF lasers use exoergic reaction: \( F + H_2 \rightarrow H + HF(v,J) \)

- Spectral images diagnose system performance
  - flow field mixing
  - inversion density (gain) mapping
  - beam diagnostics: spatial and spectral
Adaptive Infrared Imaging Spectroradiometer (AIRIS)

- **Tunable (low order) etalon operated with wide spectral range**
  - high spectral resolution, angular acceptance, and optical throughput
  - digital capacitance micrometry to control etalon spacing (wavelength) and alignment (resolution)

- **Interface to variety of IR focal plane array detectors**

- **View scene at series of individual wavelengths**
  - tune etalon to molecular features
  - sequential sampling to build hyperspectral data cube
AIRIS: Low-Order Fabry-Perot Interferometer/Imager

- At mirror spacings ~ \( \lambda \), central spot fills detector array
- Use broad-band filter to isolate free spectral range
- High angular acceptance, large aperture (36 mm)
Optical Configuration of HF AIRIS Instrument

- Spectral range = 2.6 to 3.1 \( \mu m \)
- Spectral resolution = 0.008 \( \mu m \), 8th order
- Spectral scan rate = 30 wavelengths/s
- Spatial resolution = 0.9 mm
- Magnification = 1:20 at 36 inches
- Focal plane array = 320 x 256 pixels, 30 \( \mu m \) pitch
- Object plane = 19.2 cm x 15.4 cm
- NESR = \( 10^{-5} \) W/cm\(^2\) sr \( \mu m \)
Free Spectral Range and Spectral Resolution
Spectral Responsivity of HF AIRIS

Responsivity, Counts/(W/cm²-sr-µm)

Wavelength, µm

Room Air
FILTER 1
FILTER 2

Transmission of Room Air, 1 m

H-1456 color

Responsivity, Counts/(W/cm²-sr-µm)

Wavelength, µm
F-Atom Source: 
Microwave Driven Jet (MIDJet)*

- Produces a high velocity jet of neutral gas
  - diverse source of atomic species (F, H, N, O, ...)

- No electrodes or confining dielectric vessel
  - high power (1 to 30 kW)
  - no consumable parts: low maintenance
  - “contamination-free” output
  - reactive as well as non-reactive gases
  - no diluent gas required

- Technology being developed for several applications
  - semiconductor processing
  - halogen source for high power chemical lasers
  - waste stream remediation

*U.S. Patents: 5,793,013 and 5,973,289
**MIDJet F + H₂ Reactor**

- 2.6 kW, 2.6 Torr
- Water-cooled H₂ injector

- FOV: 14.7 cm x 19.6 cm
- Images are corrected for background radiation
- Blackbody calibration of spectral response

**HF P₂(5) Emission, 2.795 µm**

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- **SF₆**
- **MIDJet**
- **H₂/He**
- **Chamber**
- **Vacuum**

**Controller and PC**
Subsonic HF($v,J$) FTIR Spectra at Two Reaction Distances

$F + H_2 \rightarrow HF(v,J) + H$

- Spectrum at 1 cm shows primarily $v' = 2,3$
- Spectrum at 9 cm shows deactivation into $v = 1$
Montage of $HF(v,J)$ Emission Images

$F + H_2 \rightarrow HF(v,J) + H$
Strategy for Population Inversion and Small-Signal Gain

- Analyze cascade pairs, i.e., $P_v(J) - P_{v-1}(J + 1)$
- $N_u = I_u/A_{ul}$
- $SSG \propto \left( N_{v,J} - \frac{g_{v,J}}{g_{v-1,J+1}} N_{v-1,J+1} \right) A_{ul}$

Example: (2,4) and (1,5) levels

$SSG \propto \left( N_{2,4} - \frac{9}{11} N_{1,5} \right) A_{2,4 \rightarrow 1,5}$
AIRIS Image of Small-Signal Gain: $P_2(5-7)$ Transitions

- Units are SSG in cm$^{-1}$
- Positive SSG observed for $P_2(4-6)$
Small Signal Gain in Subsonic Reactor: HF Fundamental Band FTIR Spectra, $v' = 2$

- Estimated gains for $v = 2 \rightarrow v = 0$ are 0.01 to 0.02 %/cm for $J' = 1$ to 5
MIDJet Supersonic Flow Reactor

- To 5 kW Magnetron
- Wave Guide
- MIDJet™
- Mixing Nozzle
- Out of Plane Optical Port
- 3" OD Flow Tube
- 2" Dia Optical Ports
- Pressure Control Valve
- Flow Transition Section
- Gate Valve
- To Roots Pump
- 8" Dia 4-way Cross
- Optical Port
Supersonic HF Flame at 8 Torr

2.650 μm

2.730 μm (P₂ (3))

2.750 μm (P₂ (4))

Relative Intensity vs. Pixel Number
AIRIS Spectra of Supersonic HF Flame

0.01 μm Interval

0.002 μm Interval

P2 (7 - 10): FTIR spectra ⇒ SSG ~ 1 %/cm
Summary

- **High-sensitivity hyperspectral IR imager**
  - 2.6 to 3.1 μm at 0.008 μm spectral resolution
  - field of regard 19.2 cm x 15.4 cm at 0.09 cm spatial resolution

- **Spectral images of F + H₂ mixing in subsonic and supersonic flowfields**

- **2-D mapping of small-signal gain**
  - results are consistent with conventional FTIR measurements

- **Spectral imaging method is a tool for:**
  - evaluation of reagent mixing schemes and reactor function
  - diagnosis of HF laser output spectral and spatial content
  - application at other HEL wavelengths
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