DFB Diode Laser Based Sensor for Isotope Ratio Detection of Methane using Continuous Wave Cavity Ring-down Spectroscopy

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02/2013
I Motivation for Studying Methane Isotopes

II Cavity Ring-down Spectroscopy

III Current Status of Work
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   · Electronic Feedback for locking lasers
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Motivation for Studying Methane Isotopes

1. Motivation for studying methane

**On Earth**
- CH$_4$ is a 80 times stronger greenhouse gas than CO$_2$ on molecule-for-molecule basis.
- Warms up atmosphere and helps form ozone.

**On Mars**
- Peaking when it's warm in some regions.
- Might be a sign of biological activities.

Fig 1. Concentrations of Methane discovered on Mars

<1> Credit: NASA
Motivation for Studying Methane Isotopes

2. Motivation for studying methane’s isotopes

Three major isotopes of methane: CH$_4$, CH$_3$D and $^{13}$CH$_4$

Methane sources on earth:

**Human activities**

(About 2/3):
- fossil-fuel extraction
- rice paddies
- Landfills
- cattle…

**Natural sources**

(About 1/3):
- wetlands, gas hydrates, permafrost, termites, oceans, freshwater bodies, non-wetland soils, wildfires…

Fig 2. Isotope ratio measurements on CH$_4$ <2>

<2> Onstott, Astrobiology, 2006
Cavity Ring-down Spectroscopy

1. CRDS

Fig 3. Schematic of pulsed CRD technique <3>

\[
\frac{I}{I_0} = \exp\left(-\frac{t}{\tau}\right) \quad \Delta k(\nu) = \frac{1}{\tau} - \frac{1}{\tau_0}
\]

Advantages of CRDS:

- High sensitivity due to long absorption length.
- Immune to intensity variations in laser.
- High throughput: individual ring down events occur on the millisecond time scale.

Cavity Ring-down Spectroscopy

2. Experimental Setup

Fig 4. Schematic of Experimental Setup
Cavity Ring-down Spectroscopy

3. DFB laser diode

- Simple and small design.
- Grating structure within the semiconductor material, to serve as the wavelength selective element and reflects light back into the cavity to form the resonator.
- Tuning is accomplished by modulating either laser current or operating temperature.

Advantages:

- Absence of any critical opto-mechanical components
- High long-term stability and reliability

Applications:

- High-resolution spectroscopy
- Laser cooling, ultra-cold atoms
- Plasma physics
- Trace gas analysis
- Combustion monitoring
- Seed laser for LIDAR measurements
- Generation of tunable CW THz radiation
1. CH$_3$D Measurements

Fig 5. Cavity ring-down spectroscopy of CH$_3$D in ~ 8.3 Torr N$_2$ buffer gas. The CH$_3$D number density was $5.2 \times 10^{13}$ molecule/cm$^3$. The temperature tuning coefficient is approximately $-12.5$ GHz/$^\circ$C, i.e. $-0.42$ cm$^{-1}$/oC.

Fig 6 (a) Line strengths of CH$_3$D in the wavelength range of 6017.5 – 6031.5 cm$^{-1}$. The total pressure in the cavity was around 8.3 Torr. The CH$_3$D number densities varied between 0.5-2.0 $\times 10^{14}$ molecule/cm$^3$.

Fig 6 (b) CH$_3$D absorption spectrum from reference (room temperature, 76.7 Torr pressure, 105 m absorption path length). Resolution is 0.01 cm$^{-1}$. A CH$_4$ absorption line is marked with an asterisk.
Table 1. Part of Line strengths of CH$_3$D in the 6017.5 – 6031.5 and 6046.5 – 6070.0 cm$^{-1}$ wavenumber region, and the possible quantum numbers of the perpendicular band $2\nu_4$(E) transitions along with their calculated absorption positions and intensities. Not all the CH$_3$D lines were assigned. Measured line strengths correspond to cm per CH$_3$D molecule. Transitions with star (*) belong to the parallel band $2\nu_4$(A$_1$), whose absorption positions and intensities were not simulated.

<table>
<thead>
<tr>
<th>Measured $v$ (cm$^{-1}$)</th>
<th>Measured $S$ (10$^{-56}$ cm/molecule)</th>
<th>Calculated $v$ (cm$^{-1}$)</th>
<th>Calculated Intensity (a.u.)</th>
<th>Transition</th>
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<tbody>
<tr>
<td>6017.590</td>
<td>0.506</td>
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<td></td>
<td></td>
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<tr>
<td>6017.706</td>
<td>2.74</td>
<td>6017.684</td>
<td>0.680</td>
<td>$^PQ_{1}(10)$</td>
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<td>6017.941</td>
<td>0.887</td>
<td>6017.767</td>
<td>0.633</td>
<td>$^PQ_{6}(14)$</td>
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<tr>
<td>6018.098</td>
<td>0.553</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6018.235</td>
<td>3.40</td>
<td>6018.229</td>
<td>2.195</td>
<td>$^PQ_{1}(9)$</td>
</tr>
<tr>
<td>6018.279</td>
<td>0.644</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6018.322</td>
<td>0.541</td>
<td></td>
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<tr>
<td>6018.488</td>
<td>3.87</td>
<td>6018.586</td>
<td>0.990</td>
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<tr>
<td>6018.731</td>
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<td>6018.730</td>
<td>2.673</td>
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<td>6018.811</td>
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<td>6019.053</td>
<td>4.85</td>
<td>--</td>
<td>--</td>
<td>$^Q_{R_2}(4)$ *</td>
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<tr>
<td>6019.184</td>
<td>5.02</td>
<td>6019.185</td>
<td>3.099</td>
<td>$^PQ_{1}(7)$</td>
</tr>
</tbody>
</table>
1. CH$_3$D Measurements

Pressure-Broadening Coefficients

![Graph showing pressure-broadening coefficients for N$_2$ and O$_2$]

- $\text{N}_2$: 0.065(2) cm$^{-1}$/atm
- $\text{O}_2$: 0.060(1) cm$^{-1}$/atm

Pressure-Shift Coefficients

![Graph showing pressure-shift coefficients for N$_2$, O$_2$, and CO$_2$]

- $\text{N}_2$: -0.012(1) cm$^{-1}$/atm
- $\text{O}_2$: -0.012(1) cm$^{-1}$/atm
- $\text{CO}_2$: -0.013(1) cm$^{-1}$/atm

Fig 7. The $\text{N}_2$ (square and solid line) and $\text{O}_2$ (circle and dash line) pressure-broadening coefficients (HWHM) of the CH$_3$D absorption line at 6017.941 cm$^{-1}$. The scattering symbols are measurements and the lines are linear fits. The slope of the linear fit is defined as pressure-broadening coefficient for HWHM.

Fig 8. The $\text{N}_2$ (square and solid line), $\text{O}_2$ (circle and dash line), and $\text{CO}_2$ (triangle and dotted line) pressure dependence of the CH$_3$D absorption peak at $\sim$ 6032.443 cm$^{-1}$. The scattering symbols are measurements and the lines are linear fits. The slope of the linear fit is defined as pressure-shift coefficient.
2. CH$_2$D$_2$ Measurements

Fig 9. CRDS of CH$_2$D$_2$ absorption spectra in 16 Torr N$_2$ buffer gas measured by 6 different DFB diode lasers. The CH$_2$D$_2$ number density was 9.87x10$^{13}$ molecule/cm$^3$. 
3. Electronic Feedback for locking lasers

Why do we want to lock the laser:

1. Reduced absorption cross section error
   \[ \sigma(\nu) = \frac{\Delta k(\nu)}{N \cdot c} \]

2. Improved cavity transmission
   \[ T_c = \frac{T^2}{(1 - R)^2} \cdot \frac{1}{1 + 2\pi \tau \cdot \Delta \nu} \]

![Fig 10. Schematic of 1f WMS feedback system](image-url)
3. Electronic Feedback for locking lasers

Fig 11. Detector output voltage of single pass cell filled with ~8torr 98% CH$_3$D at different laser driver current

Fig 12. Mixer output variance with laser temperature tuning at different laser driver current
3. Tuning PID control

Fig 13. Feedback signal jitter with different PID total gain

Fig 14. Examples of how modulation amplitudes affect the slope mixer output vs slow input.

Fig 15. Optimal modulation amplitude
3. Tuning PID control

Fig 16. Comparison of laser jitter when using feedback with different PID parameters

<table>
<thead>
<tr>
<th>PID parameters</th>
<th>Mean / MHz</th>
<th>Standard Deviation / MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>No feedback applied</td>
<td>12.75845</td>
<td>4.3672</td>
</tr>
<tr>
<td>Proportional feedback only</td>
<td>-3.25909</td>
<td>1.93233</td>
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<tr>
<td>Larger Proportional feedback</td>
<td>-1.46707</td>
<td>1.25413</td>
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<tr>
<td>Ziegler-Nichols Method</td>
<td>-0.77357</td>
<td>1.44293</td>
</tr>
<tr>
<td>Tyreus-Luyben Method</td>
<td>-0.00046</td>
<td>0.18393</td>
</tr>
</tbody>
</table>
4. Temperature Tuning System

(1) Previous fixed current method

U is controlled by D/A and PC.
Temperature can be get from Steinhart Equation
\[ 1/T = C_1 + C_2 \ln (R) + C_3 [\ln (R)]^3 \]
Where \( C_1 = 1.1292 \text{E-3}, \ C_2 = 2.3411 \text{E-4}, \ C_3 = 8.7755 \text{E-8}, \ I = 100 \ \mu\text{A}, \ R = U / I. \]

(2) New voltage divider method

Instead of a fixed I, we used a voltage divider, with the thermistor in series with fixed resistor R', and both thermister R and fixed resistor R' are driven by a fixed voltage source U'. The output voltage will be proportional to R'. \[ R = R' \times U / (U' - U) \]
4. Temperature Tuning System

Fig 17. Comparison of two methods of temperature tuning
Future Plans

I. Super narrow linewidth DFB lasers
II. Electronic feedback and temperature tuning on all lasers
III. Implement cavity locking with predicted wavelength shift
Acknowledgements

- NSF
- NASA
- UVa
- Dr. Yongxin Tang (Lehmann’s group)
- Dr. Yuheng Chen (Princeton University)
- Dr. Haifeng Huang (Sandia National Lab)
- Dr. Hongbin Chen (Tiger Optics Company)

Thank you!