Development of a Pulsed 2-micron Laser Transmitter for CO$_2$ Sensing from Space

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Acknowledgement: Research and development under NASA Laser Risk Reduction Program funded by NASA Earth Science Technology Office (Program Director: George Komar)
Outline

• Background
• CO₂ DIAL/IPDA Research Activities
• 2-micron Pulsed Lidar Approach for CO₂ Measurement
• 2-micron Pulsed Coherent Detection Lidar - for Mobile Ground-based CO₂ Profiling
• 2-micron Pulsed Direct Detection IPDA Lidar for CO₂ Column Measurement from Airborne Platform
• Summary
Pulsed Lidar Approach

- The National Academies has identified CO₂ measurement from space as a critical mission for study of climate change and global warming

- NASA has planned Active Sensing Of CO₂ Emissions Over Nights, Days, And Seasons (ASCENDS) mission for CO₂ column measurements from space

- For column measurements, the pulsed lidar approach can eliminate contamination from aerosols and clouds to yield high accuracy measurements

- The pulse approach can determine CO₂ concentrations as a function of distance with high spatial and temporal resolution, a valuable data product that is not currently available
CO₂ Absorption Line at 2-micron

Wavelength (µm)

CO₂ absorption cross section (cm²)

% (P=1013.25 mbar, T=296 K, Volume Mixing Ratio=0.1)

R30 line

Line Center

On Line

Off Line

Volume Mixing Ratio=0.1)
Atmospheric Testing—2007 Results

- DIAL at better than 0.7% precision for column over ½ hour (9000 pulses).
- Range-resolved at better than 2.4% on 500-m bins and 6.7 minutes (2000 pulses)

Improvements for 2010 Tests

- Higher pulse energy (90mJ to 250mJ) for higher SNR.
- Higher pulse repetition rate (5Hz to 10 Hz) for more pulse averaging.
- Double pulsing format for more pulse averaging and better atmospheric sampling.
- More favorable line (R30) for less water vapor bias.

Mobile Ground based High Energy CO₂ DIAL Profiling Lidar – LRRP Funded

- Smaller
- More energy
- More robust

Table Top Transceiver (Transmitter + Receiver)
90 mJ/pulse, 5 pulses/sec.
3’x4’ Optical Table
(no telescope or scanner)

Previous implementation
90 mJ per pulse

Transceiver (Transmitter + Receiver)
250 mJ/pulse, 10 pulses/sec.
5.9” x 11.6” x 26.5”, 75 lbs.; 15 x 29 x 67 cm, 34 kg
(no telescope or scanner)

Small, Robust, 250 mJ per pulse
Double Pulsed 2-µm Laser Operation

Relative Ho population in 5I7

Time (s)

Amplitude (arb. Unit)

Time (µs)

ΔFWHM = 137 ns

Double Pulses (I_{osc} = 65 A)

Time between two pulses = 150 µs
Pulsed Coherent CO$_2$ DIAL

- Pulsed 2-micron laser transmitter
  - 250 mJ/10Hz
  - Coherent DIAL
- Provide CO$_2$ profiling/column density measurement

**Transceiver**
(2 micron Laser and Receiver electronics)

**Seeding & Wave-length Locking Control**

**6” Telescope & Steering Mirrors**

**Cooling System**

**19” Electronic Rack:**
1. Laser Control Electronics 5U (8.75”)
2. DAS Analog Processing 3U (5.25”)
3. PXI Controller 3U (5.25”)
4. User Interface Computer 3U (5.25”)

**1” Electronic Rack:**
- Wavelength Locking and switching
- Laser transmitter and receiver
- Data acquisition and processing electronics
- Control Electronics
- Thermal Management

**Signals & Feedback**

**Return**

**Transmit**

**Telescope**
On-Off Return Signal

![Graph showing power spectrum density vs. range for different types of signals. The graph includes lines for Off-line, 2G, 3G, and 4G signals, with power spectrum density values ranging from -38 to -16 dB. The x-axis represents range in meters, and the y-axis represents power spectrum density.](image-url)
Pulsed 2 μm Direct Detection IPDA Lidar System for CO₂ Column Measurement

- Pulsed 2 μm lidar, with ranging capabilities, provides a direct measurement of the atmospheric CO₂ path
- Provides high sensitivity in the boundary layer with no bias from aerosol layers and clouds on the measurement accuracy
- Higher per-pulse SNR (signal-to-noise ratio) obtainable with high energy 2 μm pulsed backscatter means less reliance on multi-pulse averaging, providing potential for higher along-track spatial resolution and better measurement capability in regions of partial cloud coverage, benefiting high precision measurements.
- Operating at 2 μm results in a weighting function that peaks near the surface
- Technical Challenges for IPDA Lidar Transmitter:
  - High efficiency
  - High average power
  - Good beam quality
  - Single frequency
  - Wavelength switching and controlling
Advanced-Space Carbon and Climate Observation of Planet Earth Mission Studies

- A-SCOPE: Scientific objective: The observation of the spatial and temporal gradients of atmospheric XCO₂ with a precision and accuracy sufficient to constrain CO₂ fluxes within 0.02 Pg C yr⁻¹ on a scale of 1000 x 1000 km².

- A-SCOPE: IPDA: Instrument Parameters

<table>
<thead>
<tr>
<th></th>
<th>Transmitter</th>
<th>Receiver</th>
<th>Detector</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Transmitter</strong></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Wavelength</td>
<td>1.57 µm</td>
<td>2.05 µm</td>
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<tr>
<td>Pulse Energy</td>
<td>50 mJ</td>
<td>55 mJ</td>
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<tr>
<td>Pulse Repetition Frequency</td>
<td>50 Hz</td>
<td>50 Hz</td>
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<tr>
<td>Spectral line width</td>
<td>50 MHz</td>
<td>50 MHz</td>
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<tr>
<td><strong>Receiver</strong></td>
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<tr>
<td>Telescope diameter</td>
<td>1 m</td>
<td>1.2 m</td>
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<td><strong>Detector</strong></td>
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<tr>
<td>Quantum efficiency</td>
<td>0.74</td>
<td>0.75</td>
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<tr>
<td>Noise Equivalent Power</td>
<td>46 fW/Hz⁰.⁵</td>
<td>100 fW/Hz⁰.⁵</td>
<td></td>
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</tbody>
</table>
**Ho Laser Energy Level Diagram**

0.78/0.792µm Diode Pumping

- Heat loading (23% pump power)
- Up conversion
- Low repetition rate

Tm:fiber Laser Pumping

- Low heat loading (5% pump power)
- Less up-conversion
- High efficiency
- CW/high repetition operation

**Levels**

- **3H4**
- **3F4**
- **3H6**
- **5I7**
- **5I8**

**Pumping Wavelengths**

- 0.792µm
- 1.94µm
- 2.06µm
- 2.05µm

**Diagrams**

- Dipole-dipole interaction
- Light pump
- Laser pump

**Notes**

- 3H6 → Tm³⁺ → 5I8
- 3H4 → Ho³⁺ → 5I8
- 3F4 → Ho³⁺ → 5I7
Schematics of Lidar Transmitter

- Tm fiber laser
- Ho Oscillator
- Wavelength Control
- Ho Amplifier

Commercially available

Technology demonstrated and bread boarded; compacting and packaging is planned

Technology need to be developed/improved/demonstrated; system engineering and packaging is planned
Master Slave Laser System

The pump, oscillator, and seed beams are all mode-matched.
Ho:YLF Oscillator Performance (100 Hz)

The output pulse energy (mJ) vs. Tm:fiber laser pump power (W)
Oscillator Performance (High RR)

The output pulse energy (mJ) vs. Tm:fiber laser pump power (W) at different repetition rates:
- **1 KHz**: The graph shows a linear increase in output pulse energy with increasing pump power.
- **2 KHz**: Similar to 1 KHz, with a linear correlation.
- **7.5 KHz**: The correlation is maintained, showing consistent linear growth.
- **10 KHz**: Consistent trend, indicating a linear relationship between pump power and output pulse energy.

The data suggests a direct proportionality between the pump power and the output pulse energy across the different frequencies.
Master Oscillator-Amplifier Configuration
Breadboard Seed Lasers Schematic
Lidar Components

- Thulium-Fiber Pump Laser
- Ruggedly Packaged 80 W laser
- CO₂ DIAL/IPDA Wavelength Control
- Prototype wavelength and control layout
- CO₂ DIAL/IPDA Telescope
- CO₂ DIAL/IPDA Electronics
- CO₂ DIAL/IPDA Data Acquisition System
## 2-micron Laser Transmitter Specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Development Objectives for Current System</th>
<th>Target Objectives for Space-based System</th>
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<tbody>
<tr>
<td>Wavelength (µm)</td>
<td>2.051</td>
<td>2.051</td>
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<tr>
<td>Energy(mJ)/ Rep. Rate (Hz)</td>
<td>&gt;65mJ / 50Hz</td>
<td>65mJ / 50Hz</td>
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<tr>
<td>Pulse width (ns)</td>
<td>&lt;= 50ns</td>
<td>&lt;= 50ns</td>
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<tr>
<td>Transverse Mode</td>
<td>TEM0o</td>
<td>TEM0o</td>
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<tr>
<td>Longitudinal mode</td>
<td>Single frequency</td>
<td>Single frequency</td>
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<tr>
<td>Frequency Control accuracy</td>
<td>&lt;2MHz</td>
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</table>
Summary

• ESTO funded 2-micron Doppler lidar technology under LRRP was heavily leveraged in developing high energy, pulsed 2-micron coherent lidar system for ground-based CO₂ profiling. The system was field tested in Wisconsin during 2007

• 2-micron team has successfully developed a double-pulsed, high energy coherent DIAL system and demonstrated ground based measurement

• Accurate laser wavelength control and switching has been demonstrated, which meets the frequency stability and accuracy requirement for the CO₂ DIAL

• The NASA LaRC developed Ho pulse laser meets or exceeds the generally accepted requirements of a direct detection 2μm IPDA system, which can provide adequate CO₂ column density measurements from space

• The pulsed lidar transmitter architecture, energy, repetition rate, line width, frequency control are all suitable for space application without major scale up requirements.