Thulium-Doped Fiber Amplifier Development for Power Scaling the 2 Micron Coherent Laser Absorption Instrument for ASCENDS

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Acknowledgments

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  - **ACT-08-0021 ("CLASS ACT")**

- **Co-Investigators**
  - **Gary Spiers & Bob Menzies (JPL)**

- **LM Co-Workers**
  - **Tahllee Baynard, Mike Hinckley, Robert Nichols, John Hobbs, Ross Mackes, Nathan Woody**

CLASS ACT Primary Objective

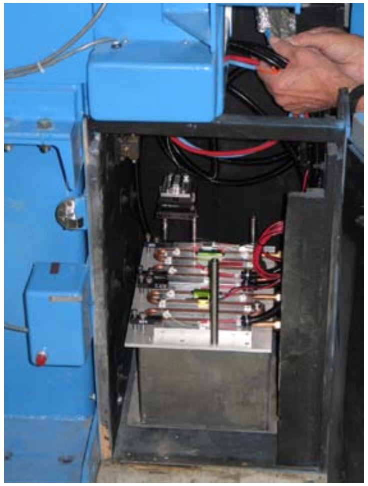
- **Demonstrate power-scaling of 2 micron (FM)CW solution for ASCENDS**
  - **From 100mW (airborne CO2 LAS) to >5W (ASCENDS with 75cm aperture), using fiber amplifier technology**
  - **Maintain absolute frequency control (total drift) <1MHz**

Power scaling identified as #1 risk for 2 micron approach
– ASCENDS Workshop (Bar Harbor, 2008) –

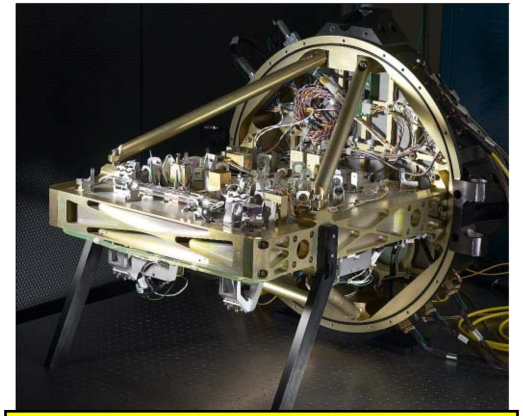
- **50x power scaling supports aperture reduction on aircraft instrument**
  - **Major reduction in instrument integration time for improved spatial resolution (Coherent CW approach is a speckle-integrated measurement)**

CLASS ACT Secondary Objectives

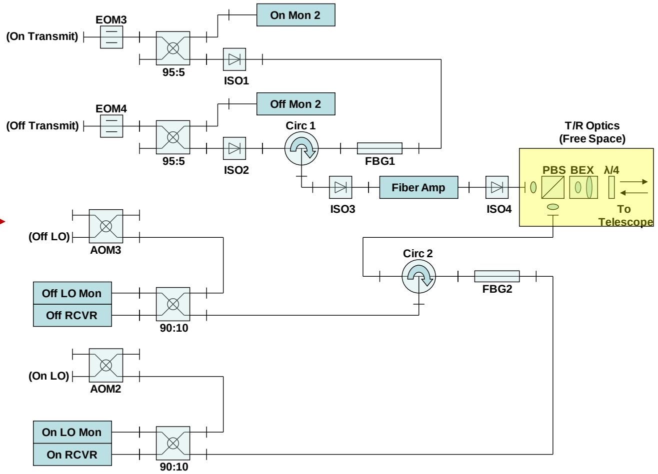
- **Perform radiation tests and sensor design study**
  - **Determine suitability of fiber amplifiers and other fiber components for ASCENDS**



- **Radiation Testing (^{60}Co) of Key Fiber Amplifier Components**



CO2 LAS Transceiver – Developed by LM for JPL airborne instrument



- **Fiber-Based Sensor Design Study**
- **Point of Departure Design from CO2 LAS to ASCENDS**

2-Step Power Scaling Approach

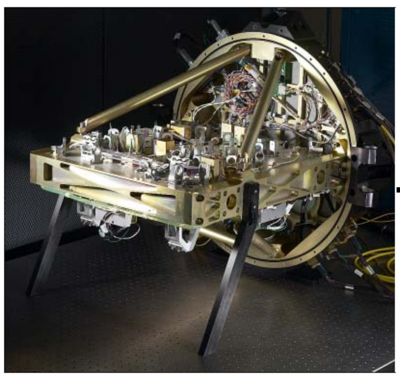
LM METEOR® Laser
•Tm,Ho:YLF (2051nm)
•Power: 100-150mW (SLM)
•20GHz tuning range
•Linewidth: 10kHz/ms (free-running)

1

Single Frequency Fiber Amplifier
•Tm:glass (2 micron operation)
•Power: >5 W out for >30mW signal input (saturated output)
•Redundant pump diodes
•Input and output optical isolation
•Test Device procured from Nufern

ASCENDS Sensor
•Power: 5W (SLM) per transmit channel
•Linewidth: < 1MHz long-term absolute frequency lock
•Aperture: 75cm dia

2



CO2 LAS Transceiver
•Power: 100mW (SLM) for On-line and Off-line transmit channels
•Linewidth: < 1MHz long-term absolute frequency lock
•Aperture: 10cm dia

Tm:Glass Fiber Amplifier (Nufern)
(enclosure removed)

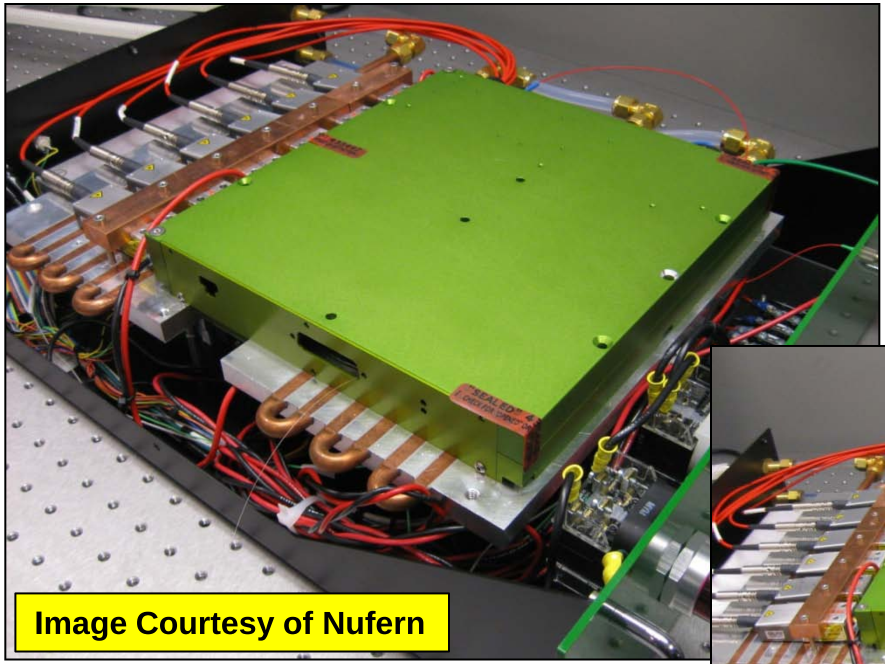


Image Courtesy of Nufern

Single frequency METEOR ® Laser

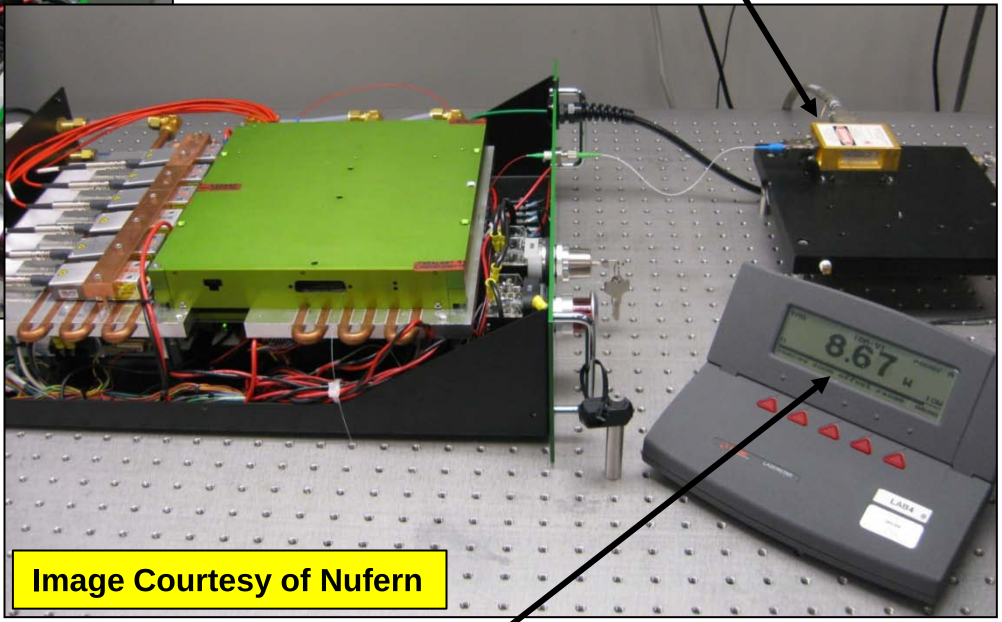
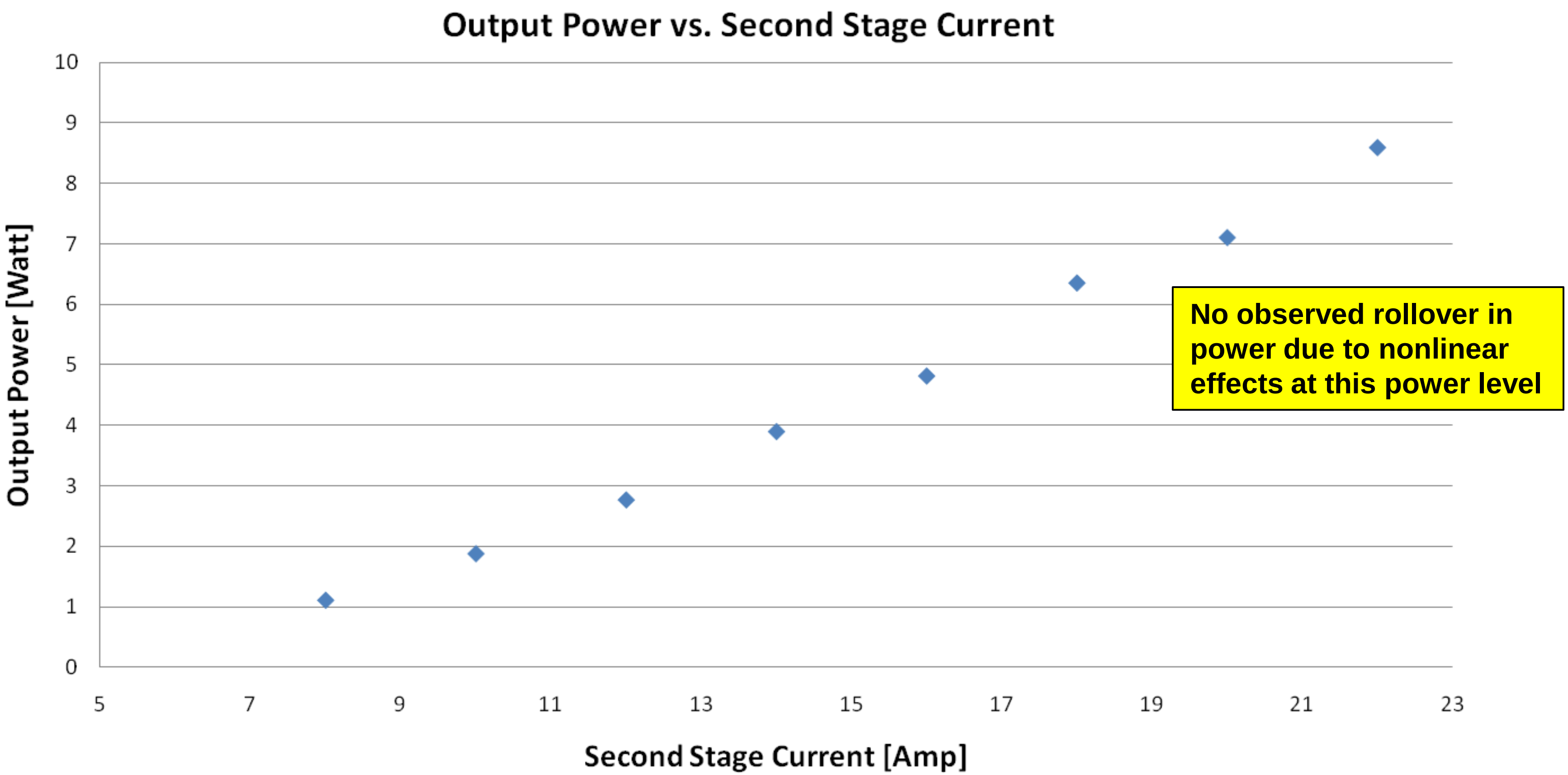


Image Courtesy of Nufern

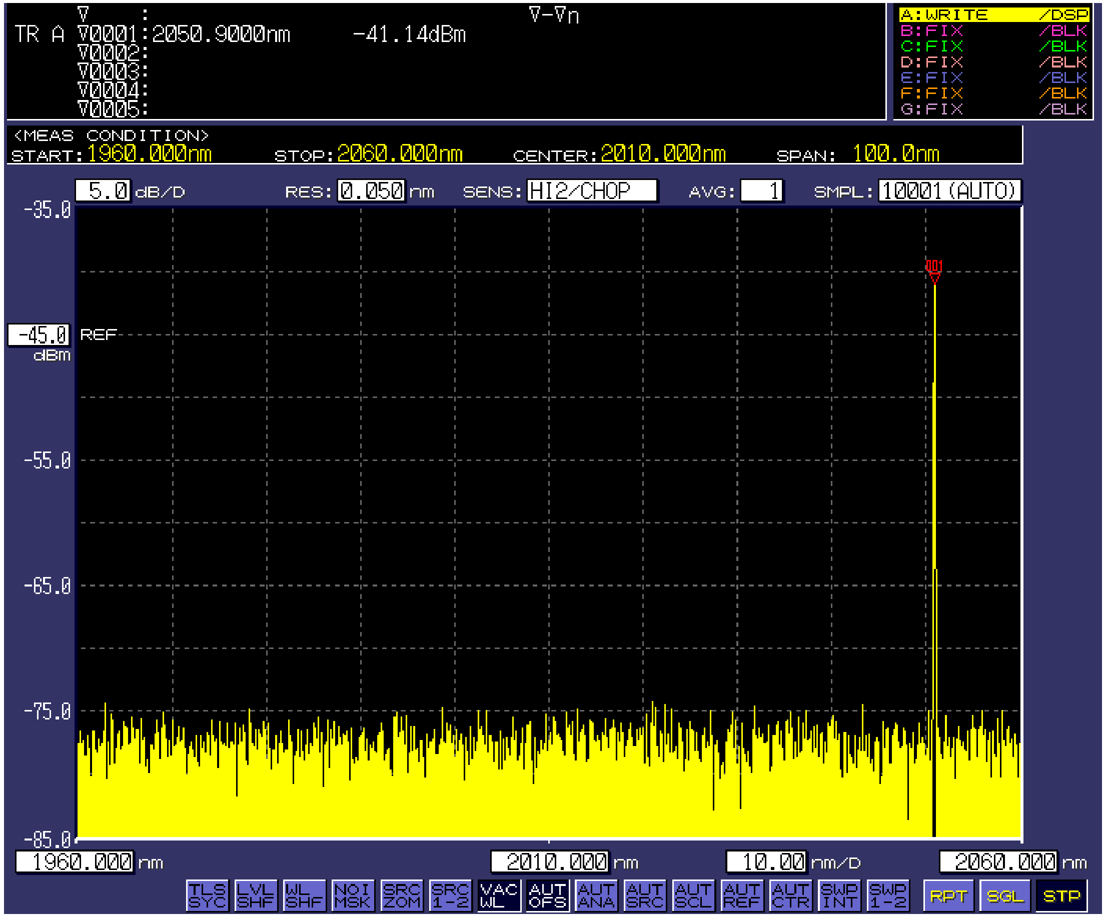
>8W output power demonstrated when seeded with 50mW single frequency METEOR ® Laser

2 Micron Amplifier Performance Results
(using stand-alone METEOR ® Laser)



Input single frequency signal power: 50mW @ 2050 .9nm

Fiber Amplifier Optical Spectrum



- **Optical Spectrum @ 8.5 W output power**
  - **Signal to Noise >38dB**
  - **No ASE or lasing observed over amplifier gain bandwidth (1960 nm to 2060 nm)**

Fiber Amplifier Optical Design

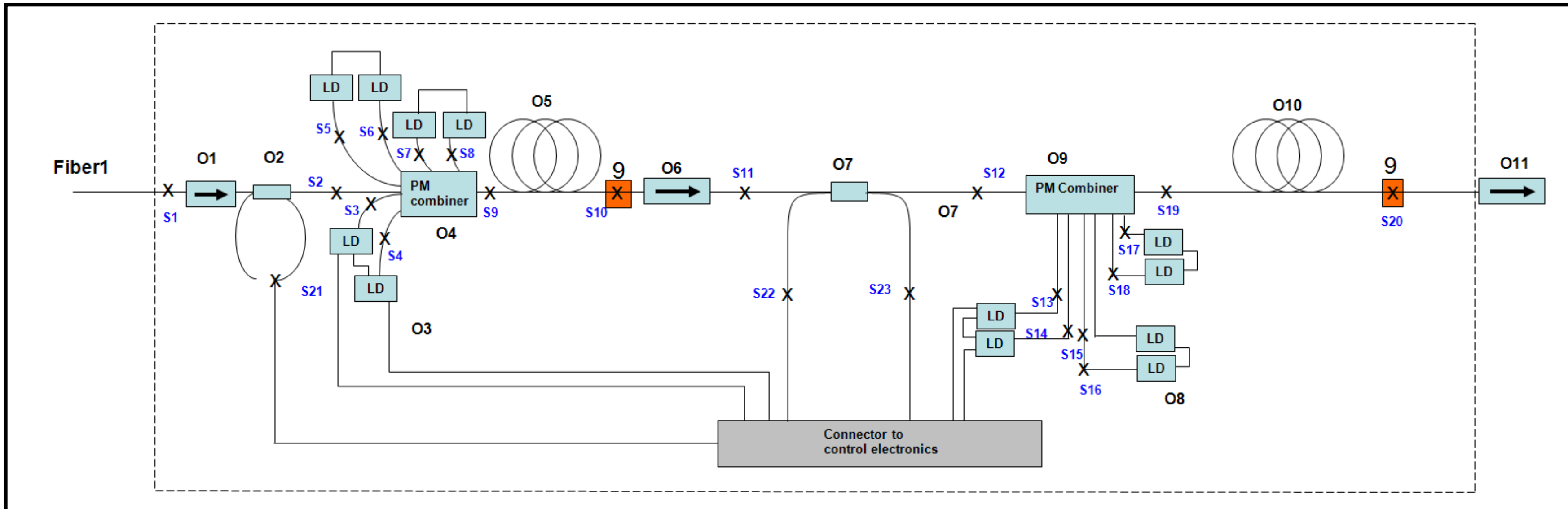


Image Courtesy of Nufern

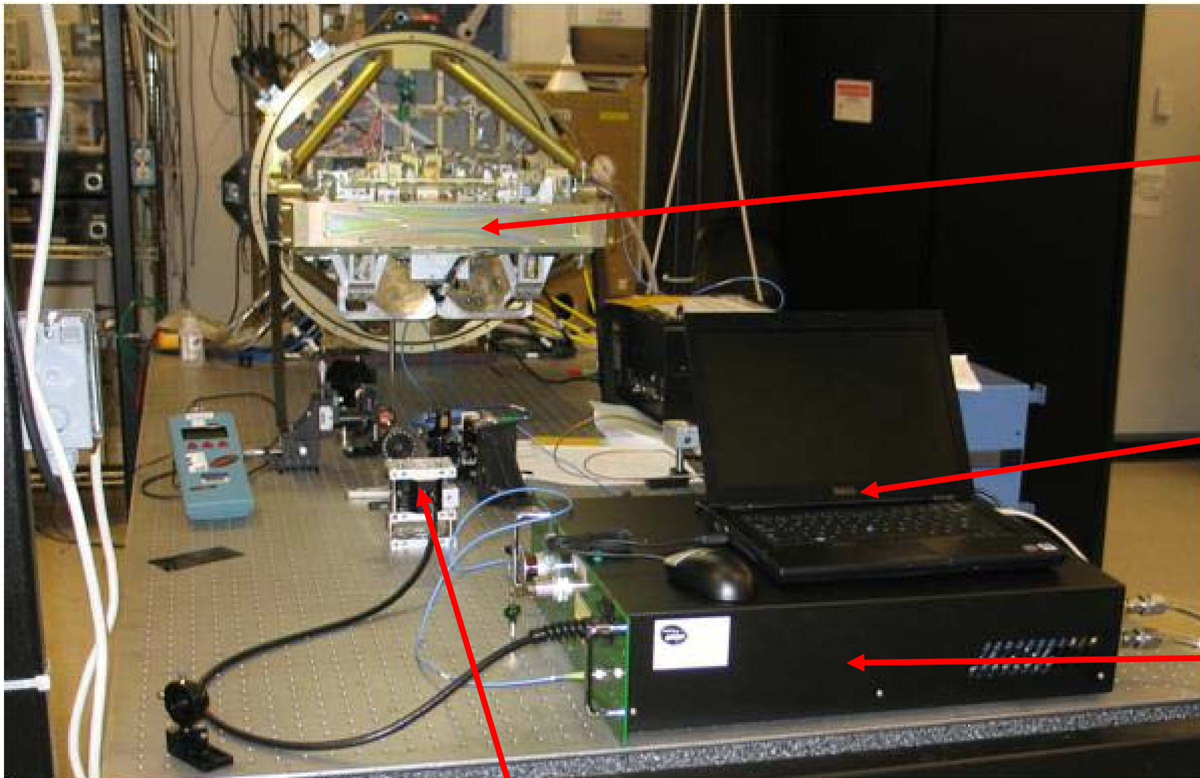
1st Stage Amp

2nd Stage Amp

Item #	Description
Fiber 1	Single mode PM1950 fiber with FC/APC connector
O1	2050nm PM isolator fiber to fiber
O2	1% 2um PM tap
O3	4W, 790nm pump diodes
O4	PM-10/130 2um 6+1x1 coupler
9	Pump dump assembly
O5	PM-TDF-10P/130-V2, 3m
O6	2050nm PM isolator fiber to fiber
O7	1% 2um PM tap
O8	20W, 783nm Pump diodes
O9	PM-10/130 2um 6+1x1 coupler
O10	PM-TDF-10P/130-V2, 3m
O11	2050nm PM isolator, fiber to free space

- **1 pair of pump diodes active at any time in each amplifier stage**
  - **Triple redundancy in pump diodes**

Fiber Amplifier Hardware in Test
(with CO2 LAS Optical Front End)



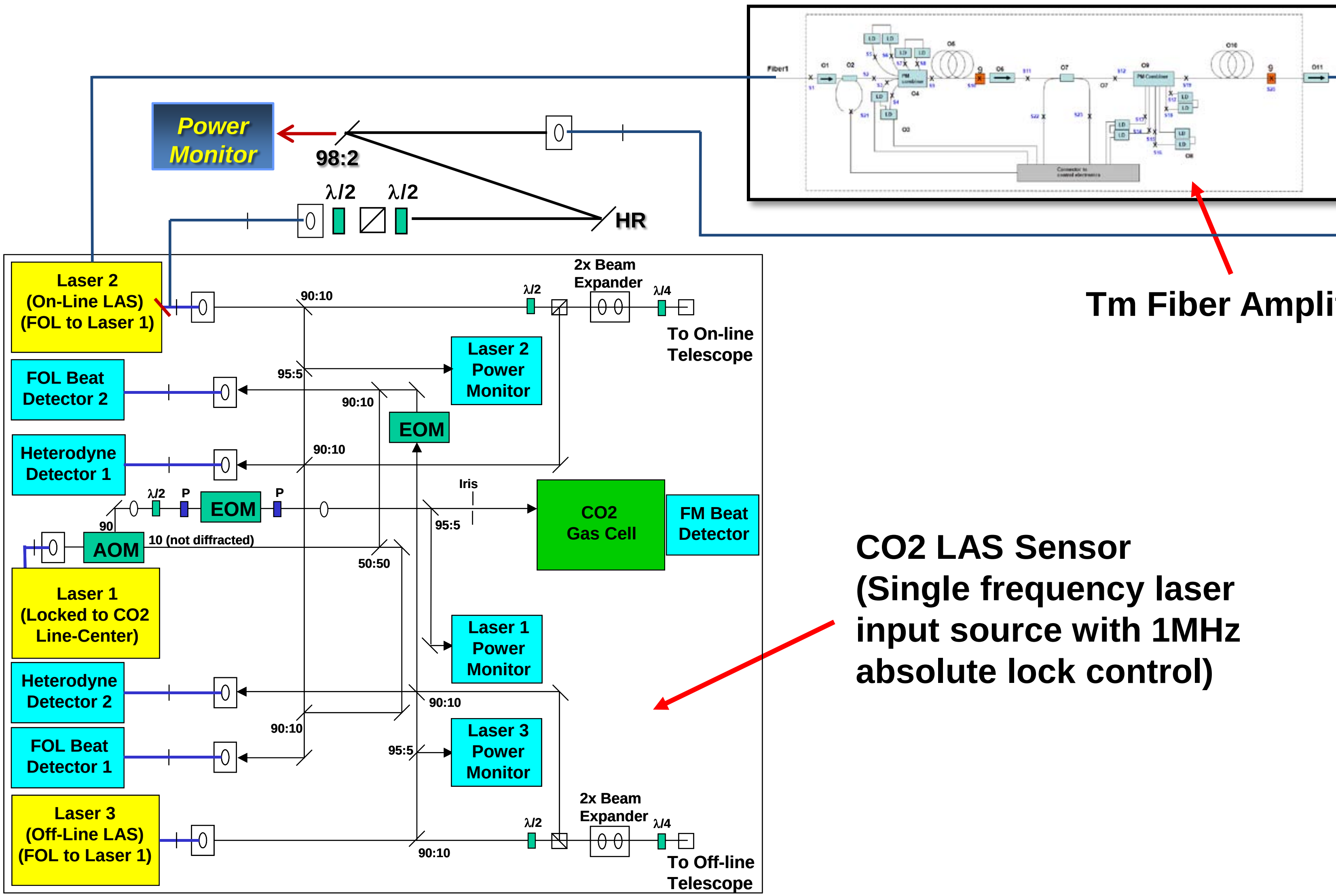
CO2 LAS Sensor (Single frequency laser input source with 1MHz absolute lock control)

Amplifier Control PC and GUI

Tm Fiber Amplifier

Amplifier output attenuated and coupled back into CO2 LAS frequency lock assembly

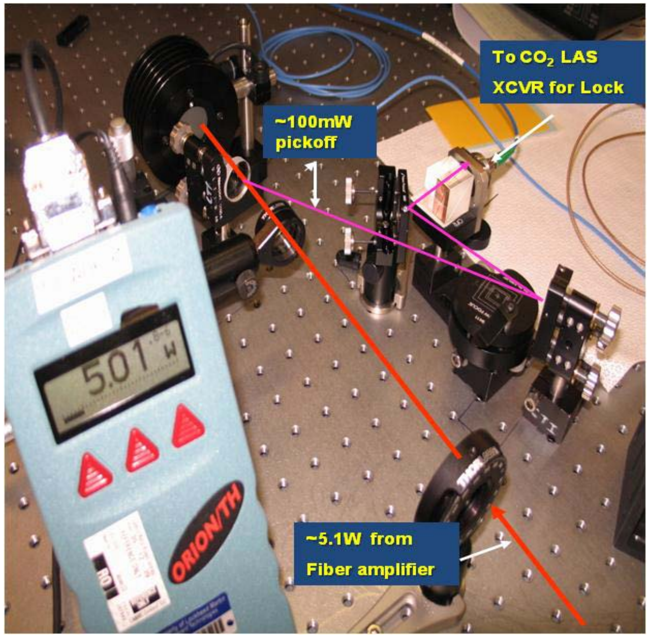
Optical Configuration using CO2 LAS Optical Front End as Input to Fiber Amplifier

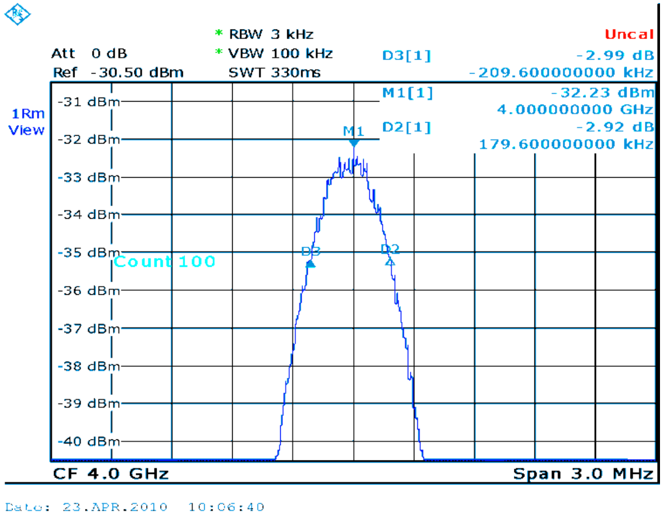


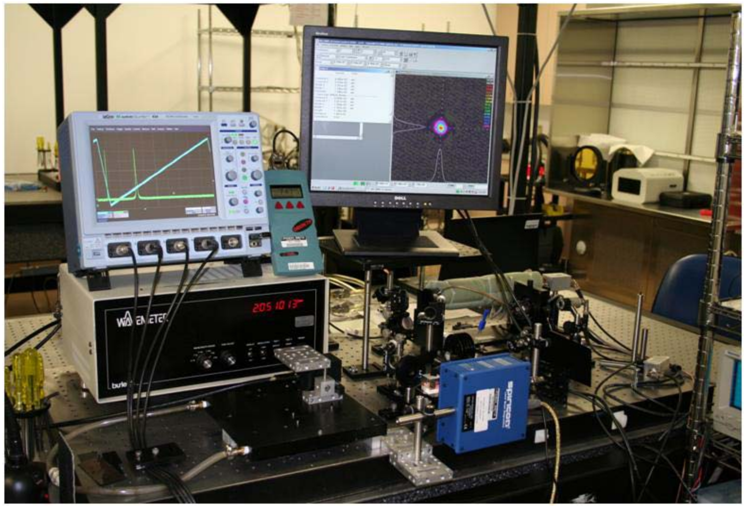
Tm Fiber Amplifier

CO2 LAS Sensor (Single frequency laser input source with 1MHz absolute lock control)

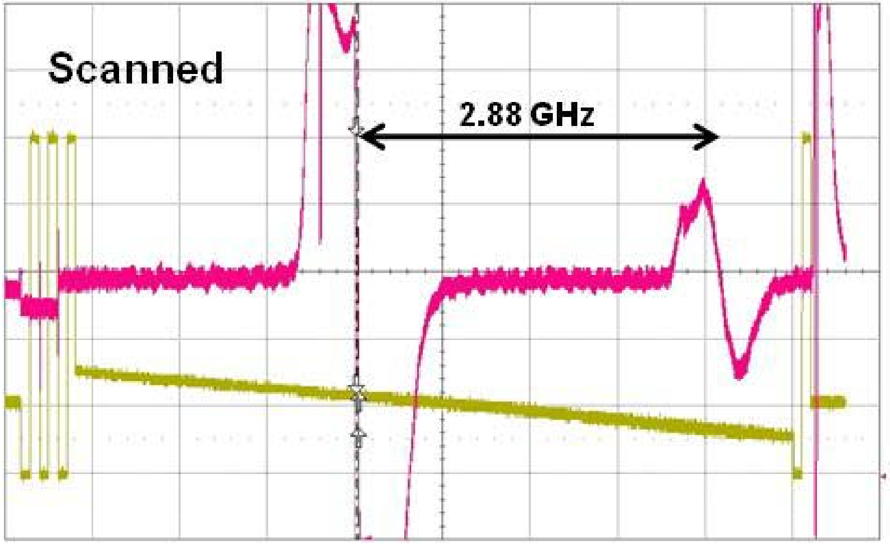
Fiber Amplifier Performance
(Power, Frequency Spectrum and Wavelength)







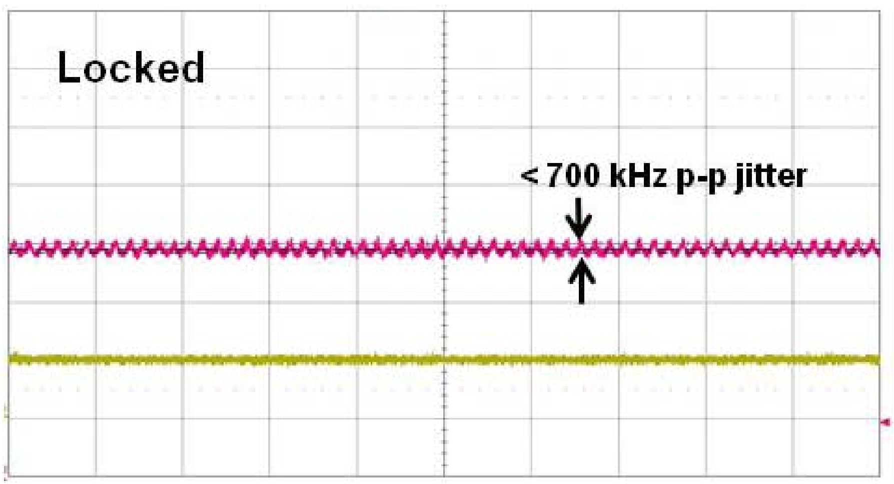
Reference MO Lock Performance



Lock Discriminant Slope Calibration

•Isotope peaks are 2.88 GHz apart

•Slope is 5.34 mV/MHz



Locked Error Signal Amplitude:

•20mV/div scale

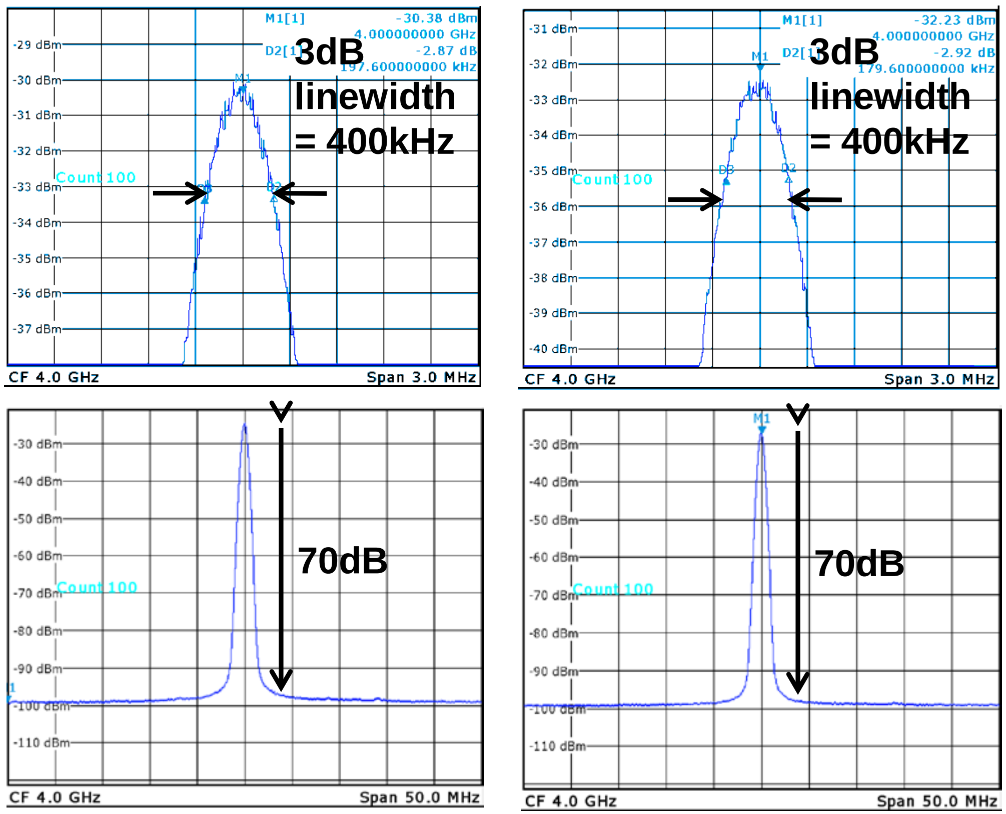
•Total amplitude p-p is <4 mV

(< 700 kHz p-p absolute stability)

•Mostly 60Hz noise that can be further filtered out

•RMS uncertainty < 270 kHz

Frequency Uncertainty between Reference Laser and 5W Amplifier Output



CO_2 LAS (100mW)

(Instrument data for comparison)

Amplified CO_2 LAS (5W)

- **Heterodyne linewidths (@ -3dB) =400kHz**
- **De-convolving linewidths of reference laser and amplifier output:**
  - **Amplifier output linewidth ~ 275 kHz**
  - **Limited by CO2 LAS lock performance**

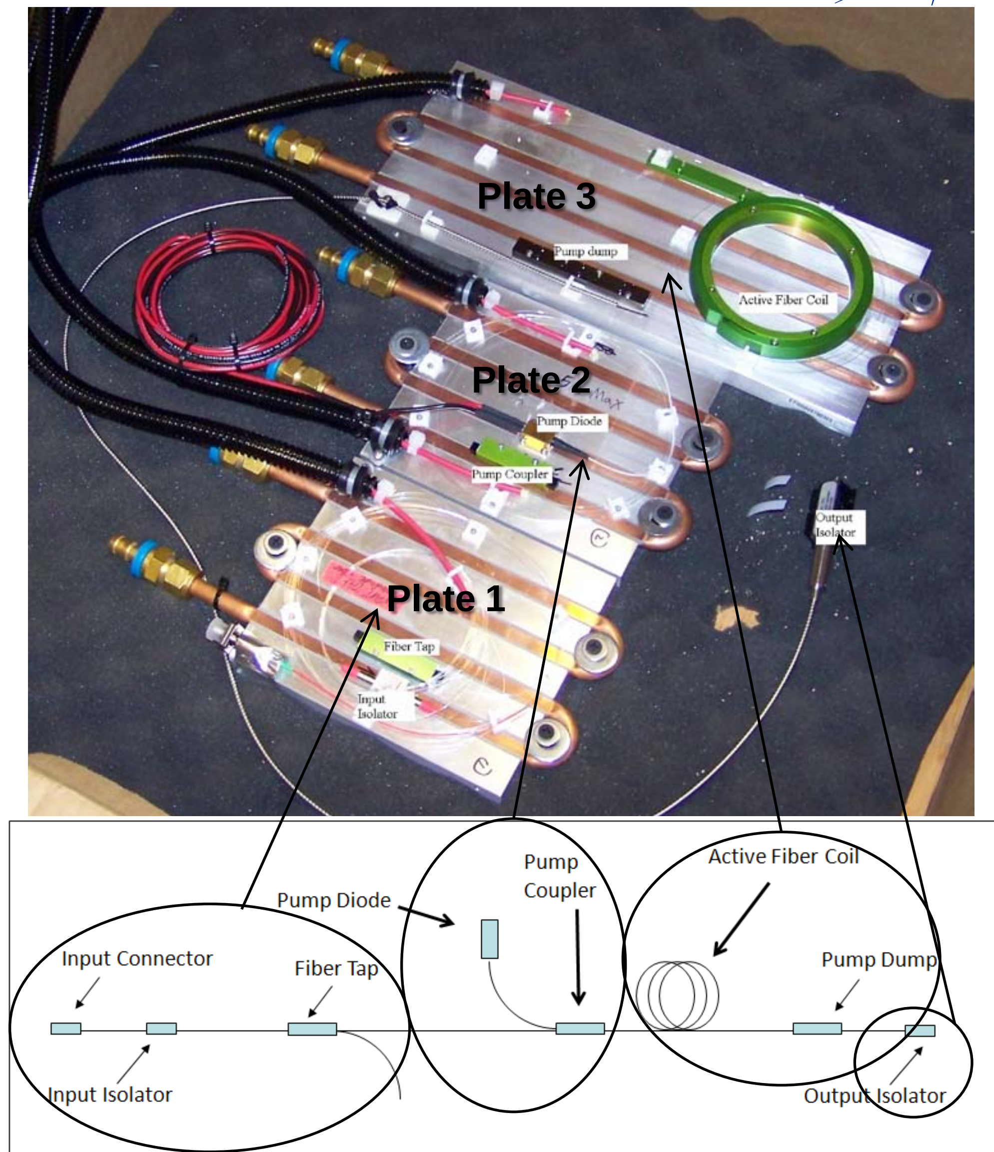
Fiber Amplifier Absolute Lock Performance

- **At >5W output power, total absolute frequency uncertainty of fiber amplifier output**
  - **< 700kHz p-p absolute reference lock + 275 kHz beat between reference laser and amplifier output (deconvolved)**
  - **~ 1MHz peak-to-peak**

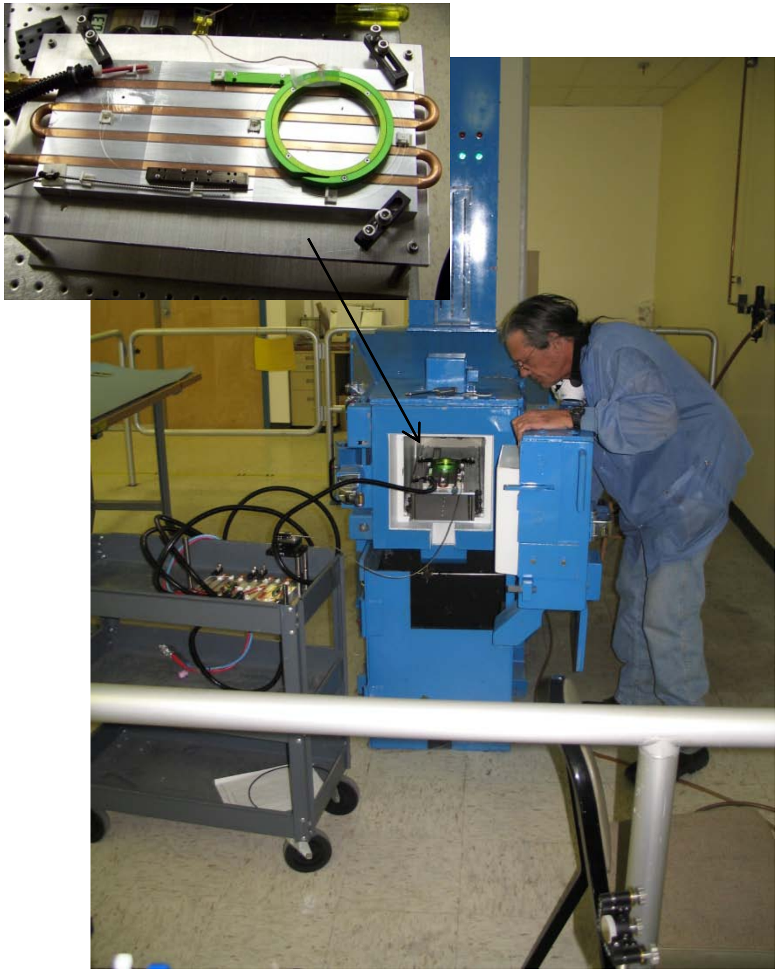
Primary Objective Met

Radiation Testing of Fiber Amplifier Key Components

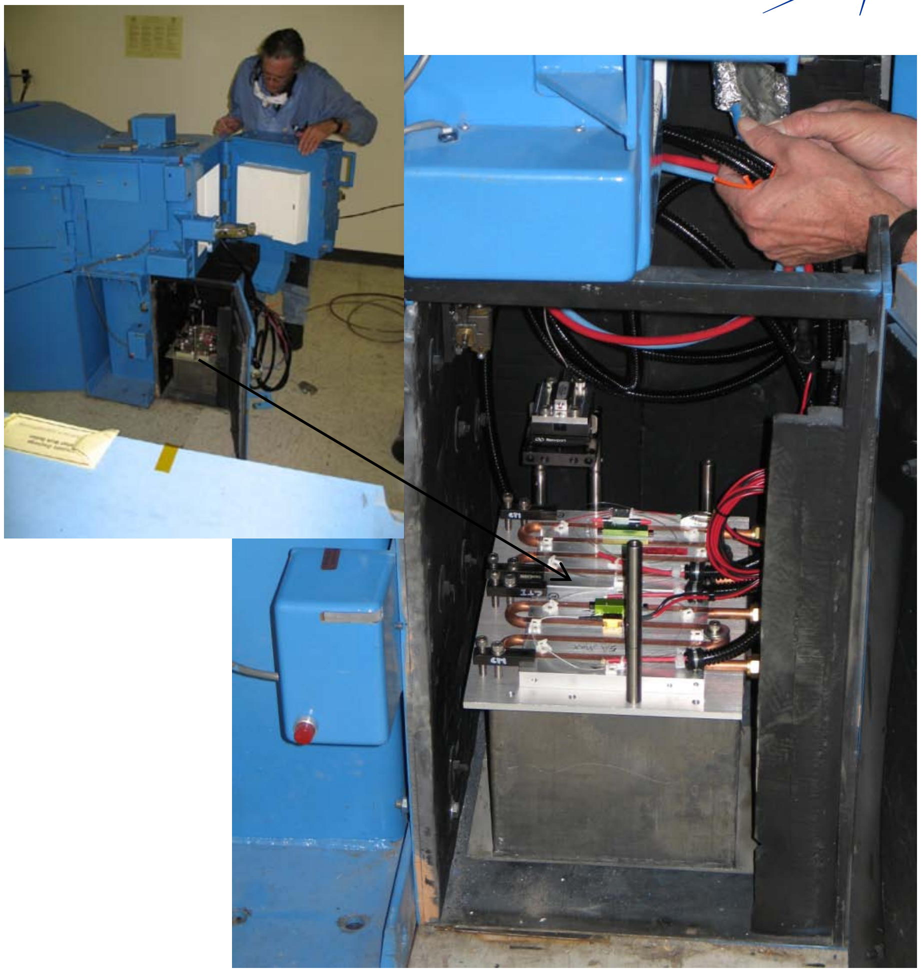
- **1W fiber amplifier tested in breadboard format with extended patch leads between major sub-assemblies**
  - Enables insertion of separate sub-assemblies into radiation chamber
  - Represents first amp stage of full 5W amplifier design



Radiation Test Configuration

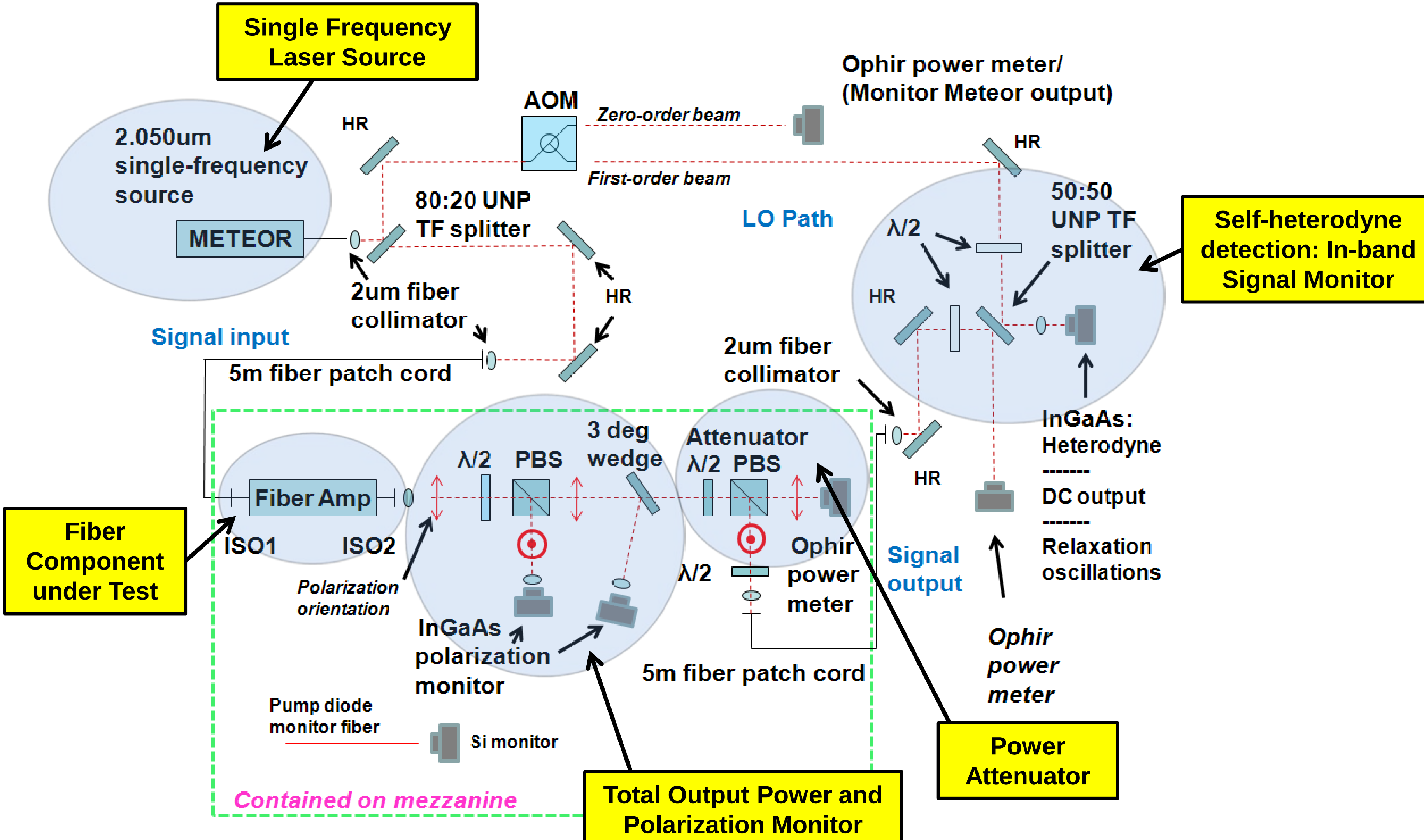


Active fiber element (Plate 3) placed in primary radiation chamber (^{60}Co)



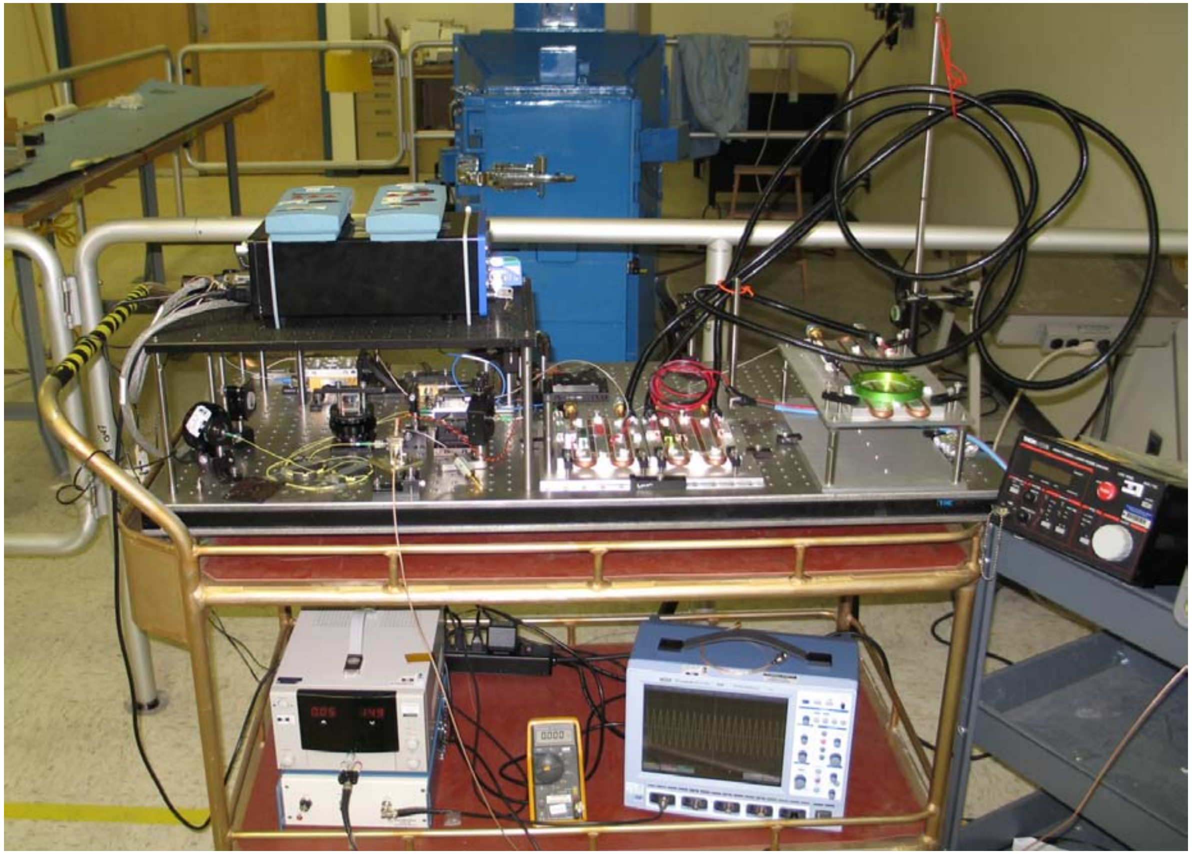
Plates 1 and 2 placed in shielded secondary (lower) chamber

Radiation Test Diagnostics Optical Assembly



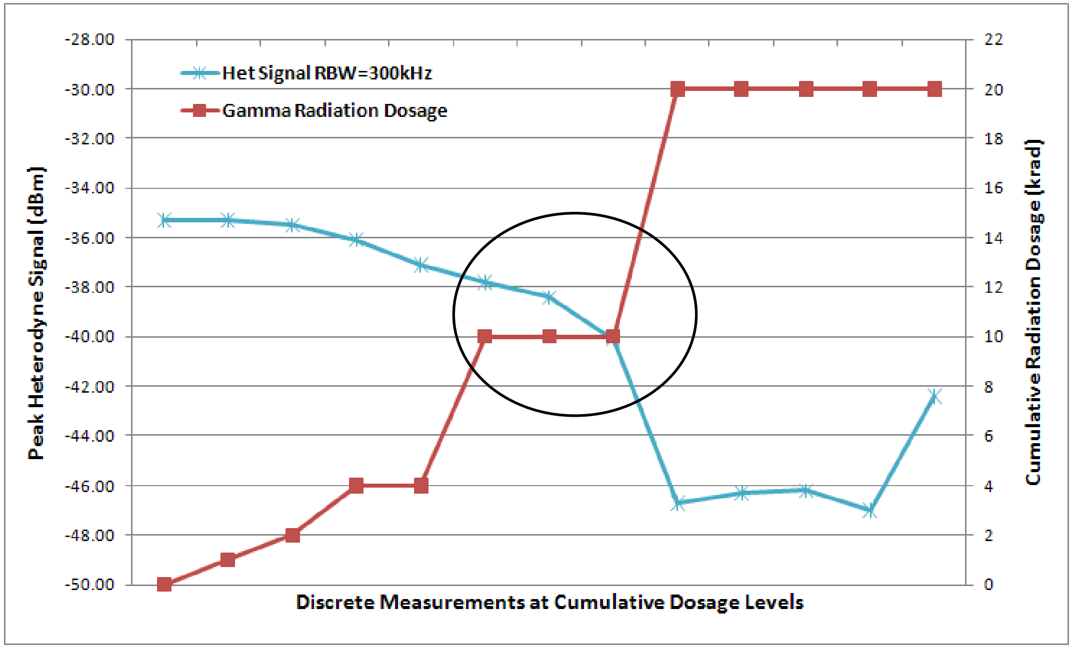
Radiation Test Configuration (2)

- **Diagnostics Optical Assembly (cart-mounted breadboard)**
  - Radiation chamber in background
  - ^{60}Co (gamma source)



Radiation Test Results – Preliminary
(Amplifier unpumped during dose accumulation)

- **Measure self-heterodyne signal (in-band power) and total output power as function of cumulative radiation dose**
- **Initial test shows 3dB in-band signal degradation at 10 krad dose and accelerated degradation at dosage beyond 10 krad**
  - **Initial test set-up susceptible to optical misalignment between data points**
  - **Re-running test with improved set-up to corroborate initial results and to test with amplifier operational during radiation dosage accumulation**

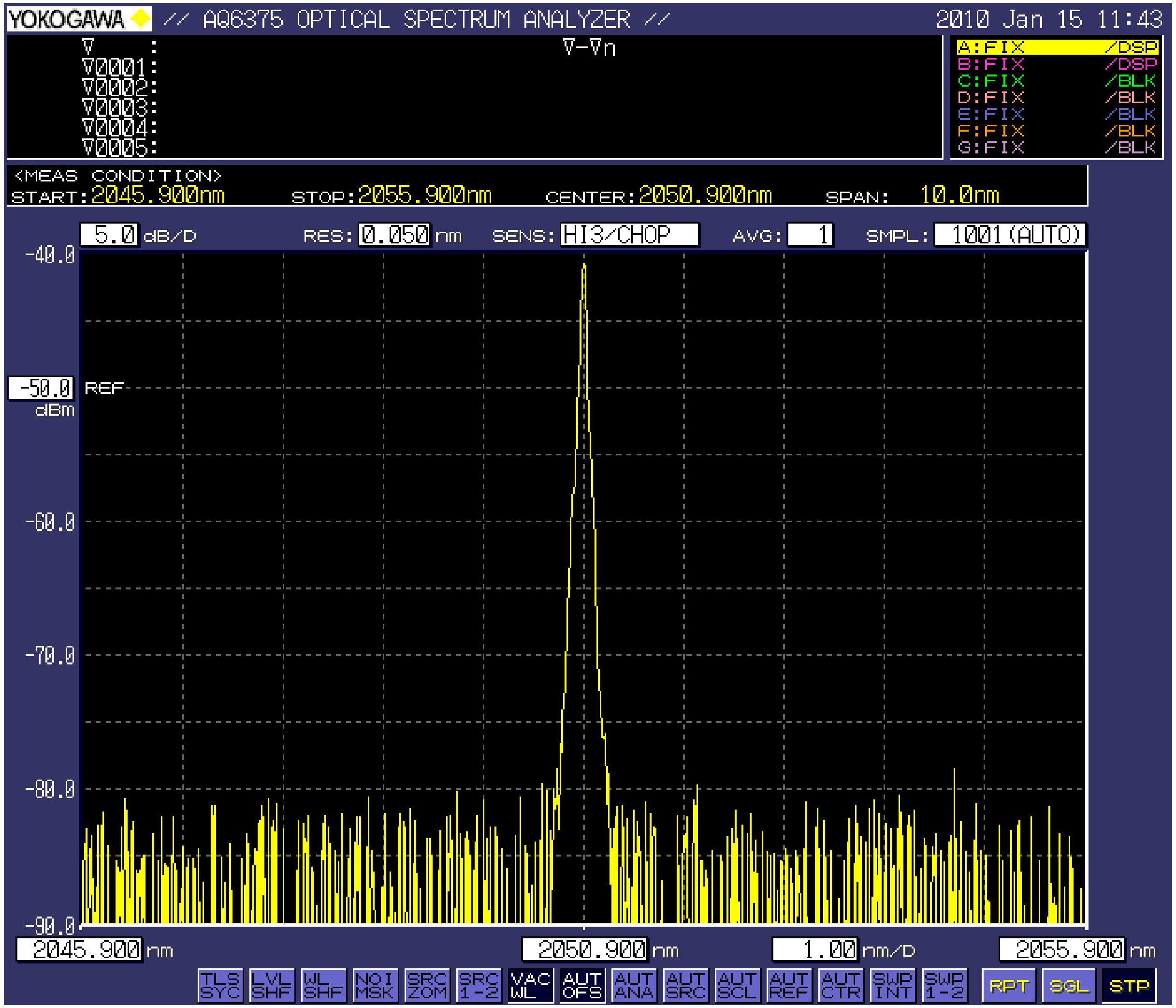


Summary

- >5W output power with <1MHz absolute frequency lock knowledge demonstrated in lab
  - #1 risk identified for 2 micron CW approach to ASCENDS
  - Power scaling also enables finer spatial resolution airborne measurements (more rapid speckle integration)
- Radiation testing of fiber amplifier key components using ^{60}Co gamma source
  - Preliminary results (non-operational during dose accumulation) indicate current fiber susceptible at cumulative doses lower than 10 krad
  - Setting up to perform equivalent test with operational fiber amplifier
  - Future test plans
    - Evaluate fiber changes for improved radiation tolerance
    - Identify and radiation-test other key fiber components for space-based sensor compatibility

BACKUP

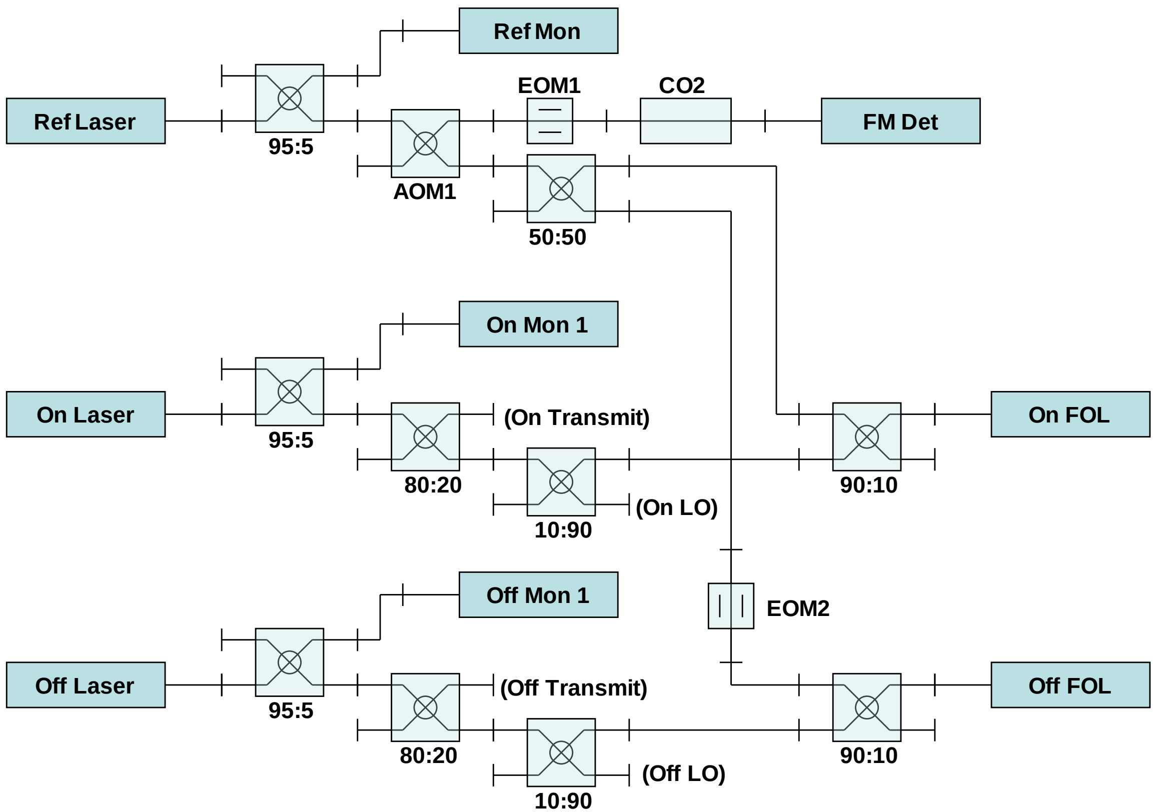
2 Micron Amplifier Performance Results



Output spectrum @ 8.5-Watt. Signal to Noise > 38dB. No ASE observed

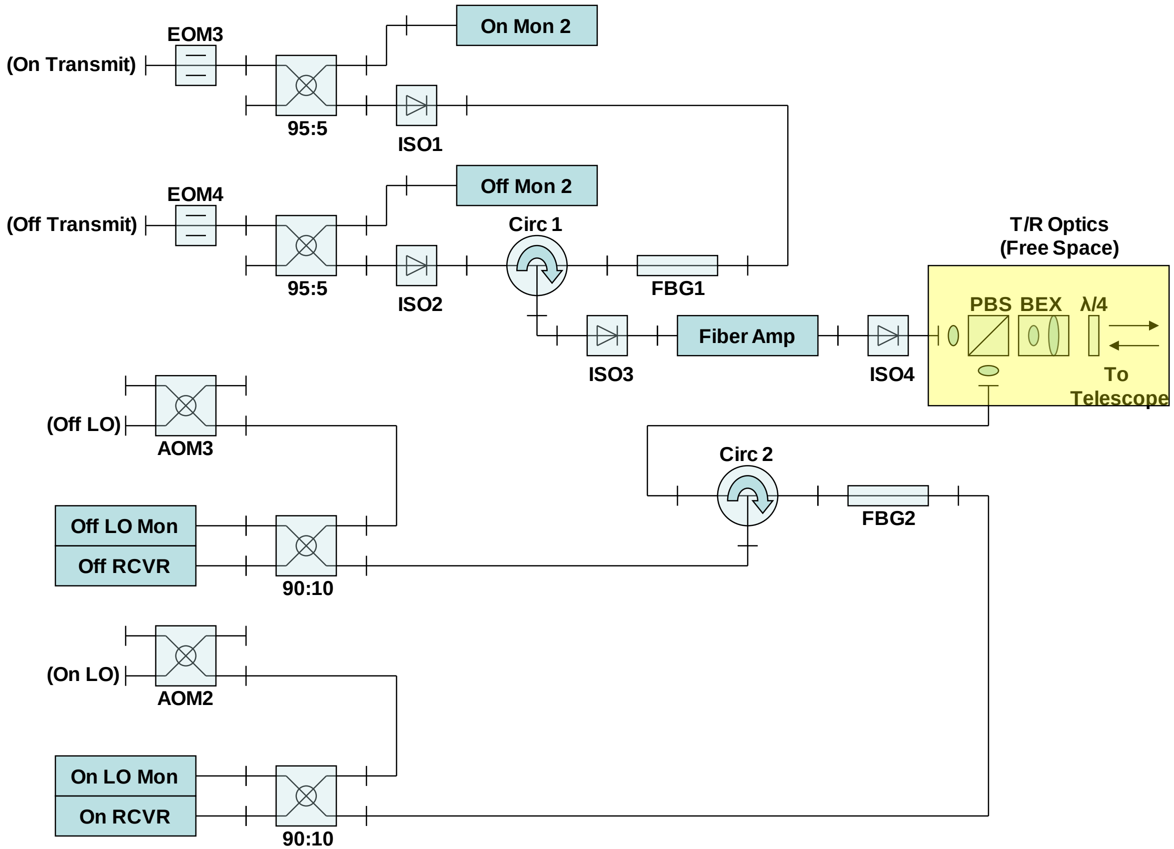
Conversion of 2 Micron CO_2 Sensor from CO2 LAS to All-Fiber Optical Assembly

- **Offers reduced SWaPT**
  - Reduced volume and reduced thermal management requirements
- **Enabled by development of <u>long-term</u> stable PM fiber couplers**
  - Based on fusion techniques



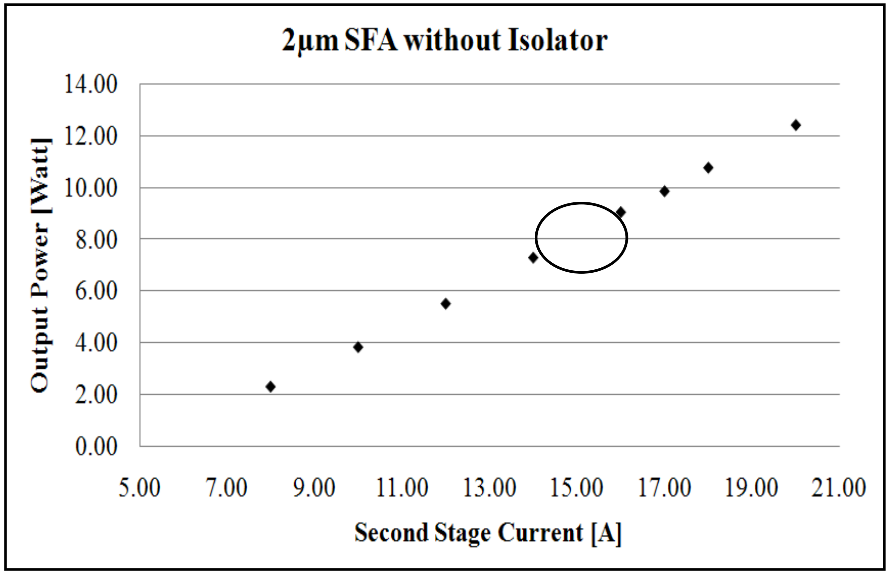
Multiplexing on and off-line channels in a single fiber amplifier assembly

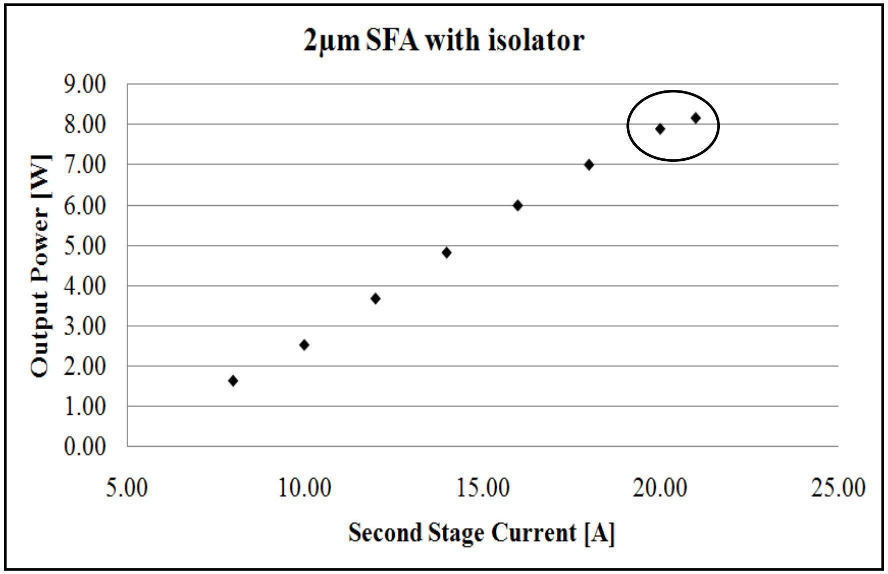
- **Provides larger common optical path for on and off-line channels**
  - **Simplifies differential absorption calibration**
- **Eliminates need for multiple telescopes – a major SWaP reduction**
- **EO modulators added for FMCW capability (range resolution)**



Fiber Amplifier Impact on Input Power Requirement

- Fiber amplifier electrical input/optical output power requirements
  - 20A, 2x1.8V (72W) supplied to pump diode for 8W output signal
  - Output measured after output optical isolator with 3dB insertion loss
  - Alternate isolator identified with 1dB insertion loss (>10W output at 20A)





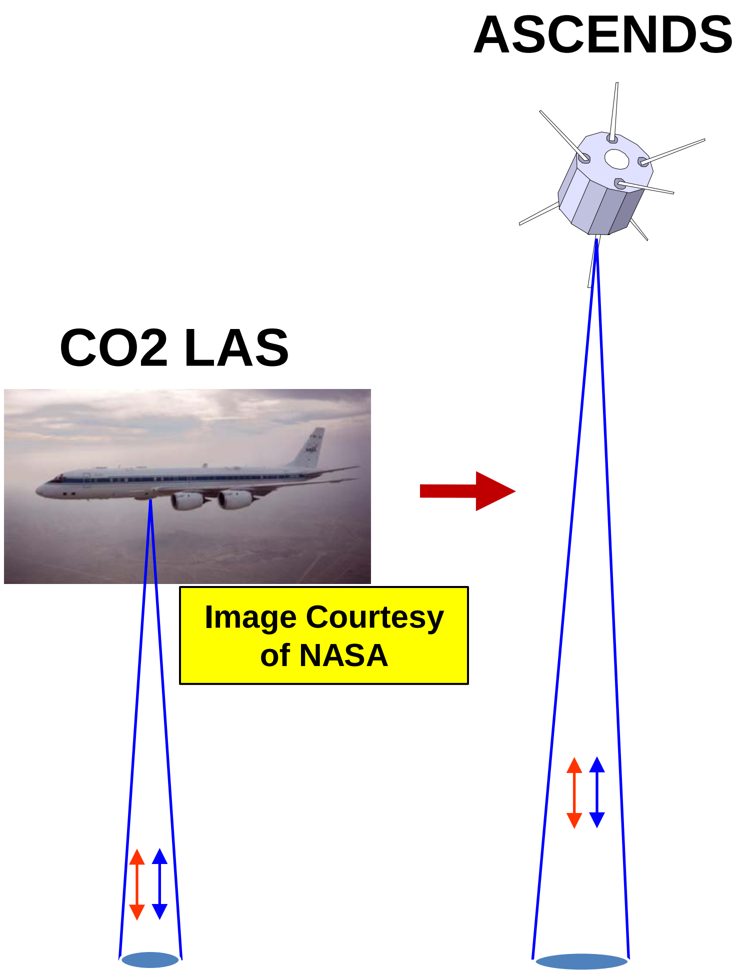
- Review space-qual pump diode driver capability
  - Determine additional power draw to operate fiber amplifier in space
- Simplified thermal management requirements will offset additional power requirement for fiber amplifier operation

Outline

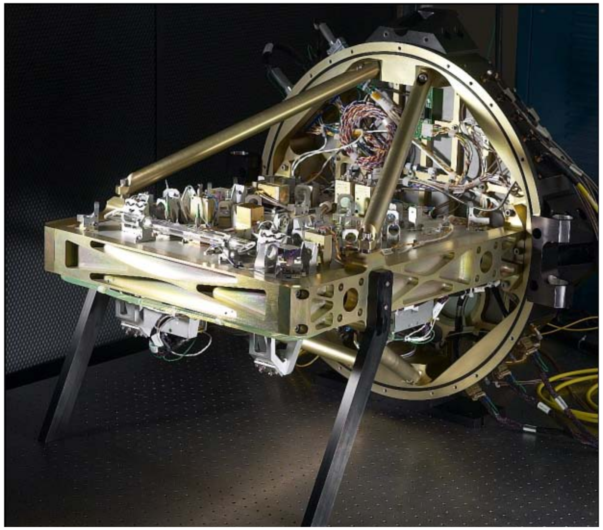
- 2 Micron CW Sensor Approach to CO_2 Concentration Measurement
- ACT Grant: Top-Level Objectives
- Fiber Amplifier Testing
- Radiation Testing
- All-Fiber Sensor Design Concept
- Summary

Concept for Global CO_2 Laser Absorption Spectrometry (LAS)

- **Transmit/receive near nadir-pointing laser beams at on and off-line wavelengths**
  - **Surface reflection (land and sea) provides Doppler-shifted return signal**
  - **Measure integrated path differential absorption (IPDA) at on and off-line wavelengths**
- **Calculate and map CO_2 concentration using additional sensor data**
  - **Column temperature profile, surface pressure, altimetry**
- **Transition sensor technology from airborne science risk reduction measurements to ASCENDS mission**
  - **Global sampling from LEO platform with <2 ppmv concentration precision and 50-100 km horizontal resolution (large scale measurements)**



Coherent Laser Transceiver for JPL's Airborne CO2 LAS Instrument



Laser Radar Transceiver – Enclosure removed, engineered for airborne operation

Support Electronics with embedded micro-controllers

Signal Processor and Computer Graphical User Interface

- **Turn-key coherent laser transceiver developed at Lockheed Martin for JPL**
  - **Lasers: Tm,Ho:YLF @ 2051nm, 100mW per transmit channel**
  - **3 on-board CW single frequency lasers (2 transmit, 1 reference)**
  - **Reference laser locked to <1MHz absolute frequency knowledge**
  - **On and off-line transmit lasers frequency offset-locked to reference laser**

Power-Scaling Approach

- **Combine LM’s 2 µm single frequency laser capability with custom Tm:glass fiber amplifier**
  - **Confine fiber amplifier architectures to support all-fiber transmitter designs**
    - **Avoid free-space optics between amplifier stages for rugged sensor design**
- **Demonstrate power scaling in two steps**
  - **With stand-alone LM METEOR® laser**
  - **With CO2 LAS sensor (frequency control front-end optics and electronics) for absolute frequency control**
- **Tm:glass fiber amplifier procured from Nufern**
  - **Single transverse mode, polarization-maintaining**
  - **Input and output optical isolators**
  - **Redundant pump diodes with 7-to-1 pump coupler**

LM's METEOR® Single Frequency Laser

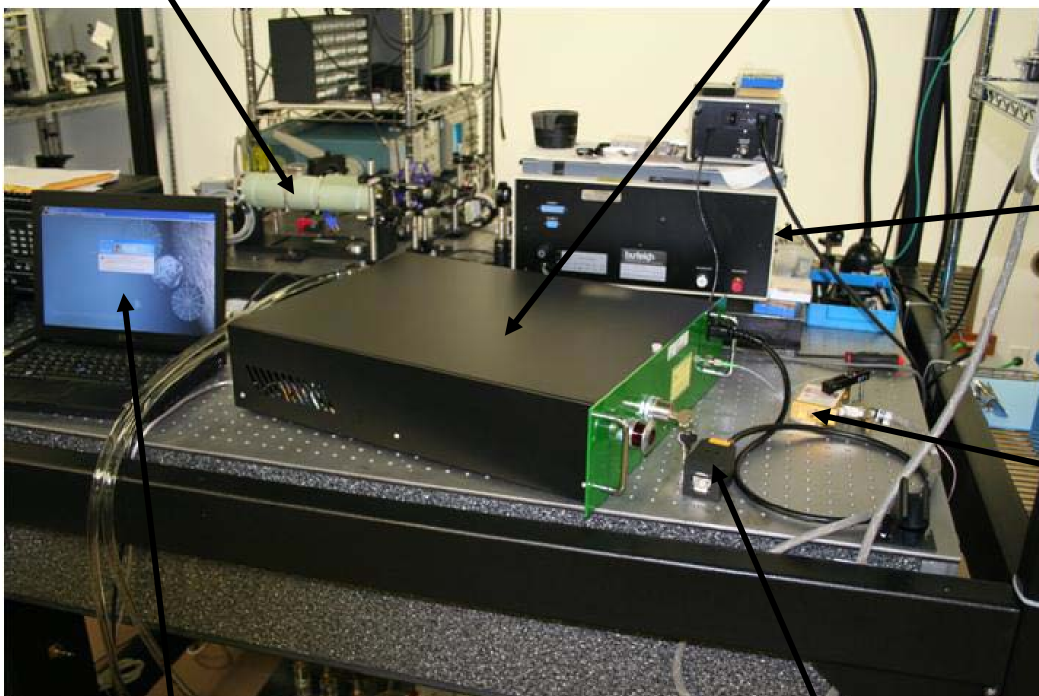
- Custom Tm,Ho:YLF METEOR® lasers developed for CO_2 LAS
  - Compact, discrete element laser cavity, PZT-tuned
  - 2051 nm operating wavelength
  - 100-150mW output power (SLM)
  - ~15 GHz frequency tuning range
  - ~10 kHz/ms linewidth (full jitter), free-running
  - All units in CO_2 LAS transceiver PZT-tuned for <1 MHz absolute frequency lock

Fiber Amplifier Hardware in Test
(Stand-alone METEOR® – Year 1 Test)

Interferometer

Tm Fiber Amplifier

Wavemeter

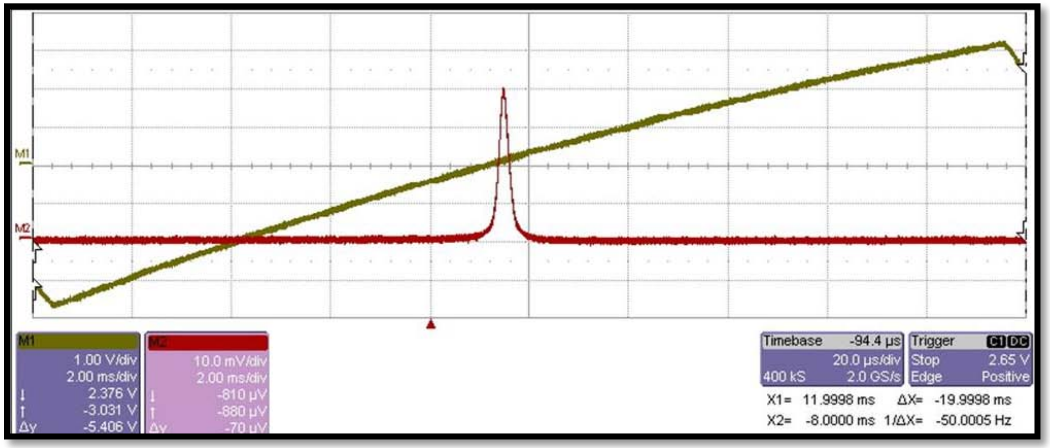


Single frequency METEOR ® Laser

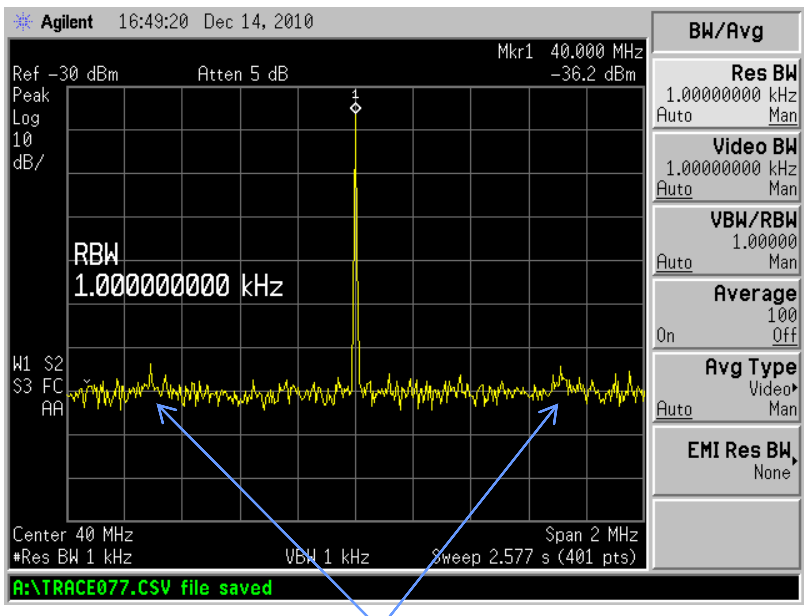
Amplifier Control PC and GUI

Amplifier Output Port with Optical Isolator

Single Frequency Operation Verification



Stand-alone Demonstration: Single frequency operation of METEOR ® laser verified with 300 MHz FSR scanning interferometer



Relaxation oscillation sidebands

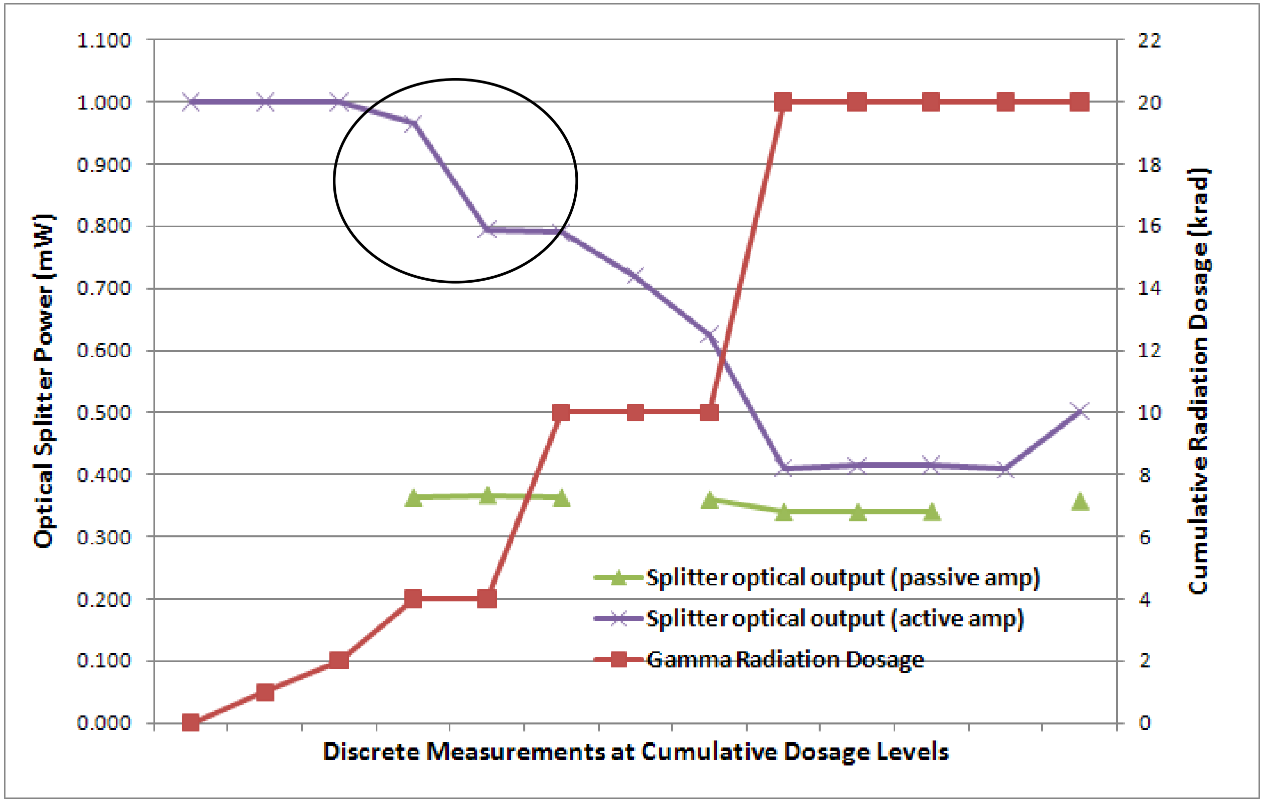
Using self-heterodyne detection: Single frequency operation of METEOR ® laser verified by monitoring relaxation oscillation tones (several hundred kHz removed from carrier)

Radiation Test Approach

- **Fiber Amplifier performance characterized before, during and after radiation dose accumulation using heterodyne detection measurement**
  - **METEOR 2 micron laser used both as LO and seed source**
  - **AOM provides frequency shift for self-heterodyne measurement**
- **Seed transmitted by un-pumped amplifier compared with pumped amplifier output**
  - **Baseline Measurement: In-band heterodyne signal strength compared with same total power incident on output power meter**
  - **Radiation Test: For fixed attenuation, in-band heterodyne signal and total amplifier output power monitored throughout active test (before, during, and after dose accumulation)**
  - **Assesses radiation tolerance of first stage fiber amplifier under operational conditions**

Radiation Test Results – Preliminary (2)

- **Optical splitter power monitors constant fraction of total power output from fiber amplifier (not just in-band amplified signal)**
  - **Amplifier on (pumped): Total output power follows similar trend as in-band signal**
  - **Amplifier off (unpumped): Total output power stays approximately unchanged**
  - **Radiation dosage appears to change fiber gain, not transmission loss of fiber**
  - **Drop in active amp power after 4 krad dosage requires further investigation**



Radiation Test Results – Preliminary
(Amplifier unpumped during dose accumulation)

- **Self-heterodyne signal (in-band power) data shows initial degradation at low cumulative dosage (>2 krad) and major degradation above 10 krad dosage**
  - **Some recovery in in-band signal seen after running amplifier for 4 hours after 20 krad cumulative dosage**
  - **Continued signal degradation after 10 krad dosage requires further investigation**