Fiber-based, trace-gas, laser transmitter technology development for space

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NASA-GSFC

Mike Rodriguez, Graham Allan, Bill Hasselbrack - Sigma Space Corp.

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Billy Mamakos – Design Interface, Inc.

Brian Bean – SOBO, Inc.

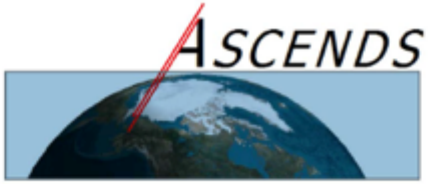
Maura Tokay – SSAI

Outline

- Overview
- Seed Module
- Pre-Amplifier
- Power Amplifier
- Conclusions

Overview

NASA's ASCENDS Mission



Active Sensing of CO_2 Emissions over Nights, Days, and Seasons (ASCENDS) Mission

Science Mission Definition Study

Draft

ASCENDS Ad Hoc Science Definition Team:

Kenneth W. Jucks,[1] Steven Neeck,[2] James B. Abshire,[3] David F. Baker,[4] Edward V. Browell,[5] Abhishek Chatterjee,[6] David Crisp,[7] Sean M. Crowell,[8] Scott Denning,[9] Dorit Hammerling,[10] Fenton Harrison,[11] Jason J. Hyon,[12] Stephan R. Kawa,[13] Bing Lin,[14] Byron L. Meadows,[15] Robert T. Menzies,[16] Anna Michalak,[17] Berrien Moore,[18] Keith E. Murray,[19] Lesley E. Ott,[20] Peter Rayner,[21] Otilia I. Rodriguez,[22] Andrew Schuh,[23] Yoichi Shiga,[24] Gary D. Spiers,[25] James Shih Wang,[26] and T. Scott Zaccheo.[27]

April 15, 2015

Avail from:
http://cce.nasa.gov/ascends_2015/index.html

National Aeronautics and Space Administration | + NASA Homepage + NASA Carbon Cycle and Ecosystems

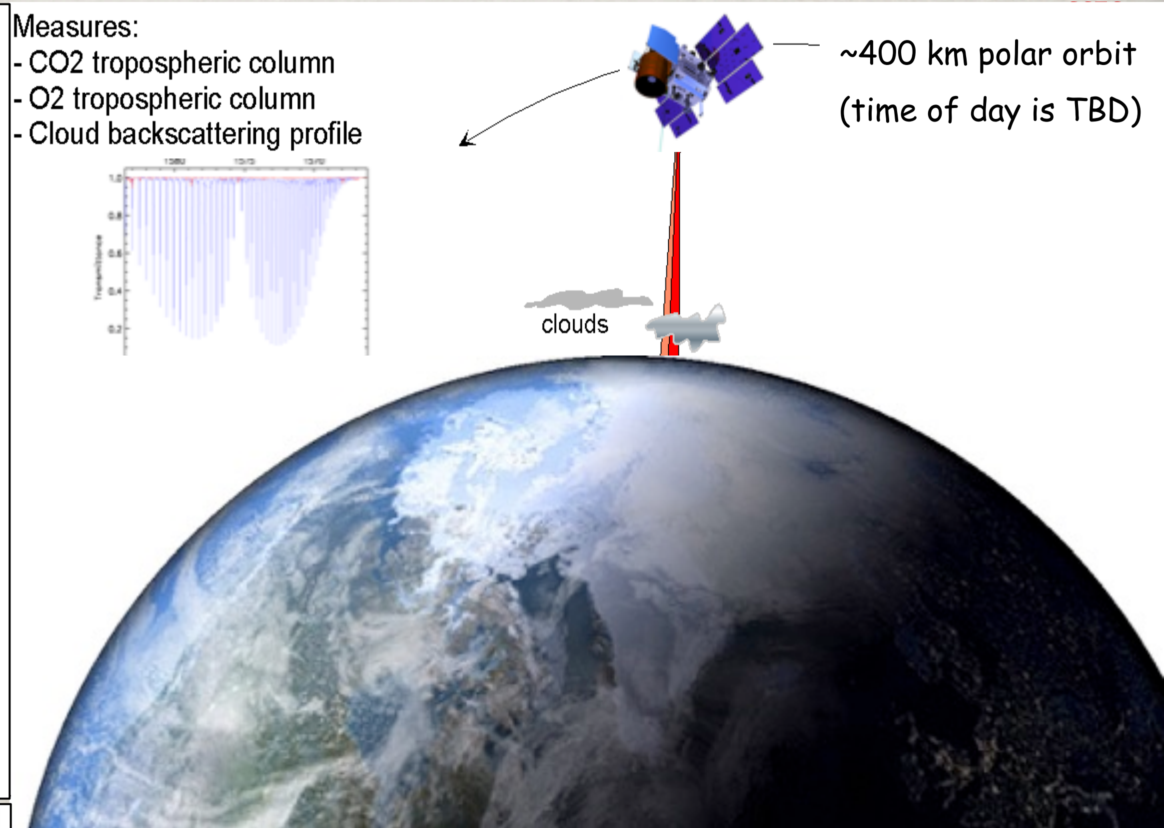
ASCENDS 2015 Workshop

Home | Agenda and Presentations | Participants | ad hoc Science Definition Team

ASCENDS Workshop
June 19, 2015
California Institute of Technology

This workshop will be held after the *11th International Workshop on Greenhouse Gas Measurements from Space* at California Institute of Technology, Pasadena, California, USA, Friday, June 19th.

View their website for logistical information: https://sites.google.com/site/iwggms11/



Requirements for CO_2 Mixing Ratio:

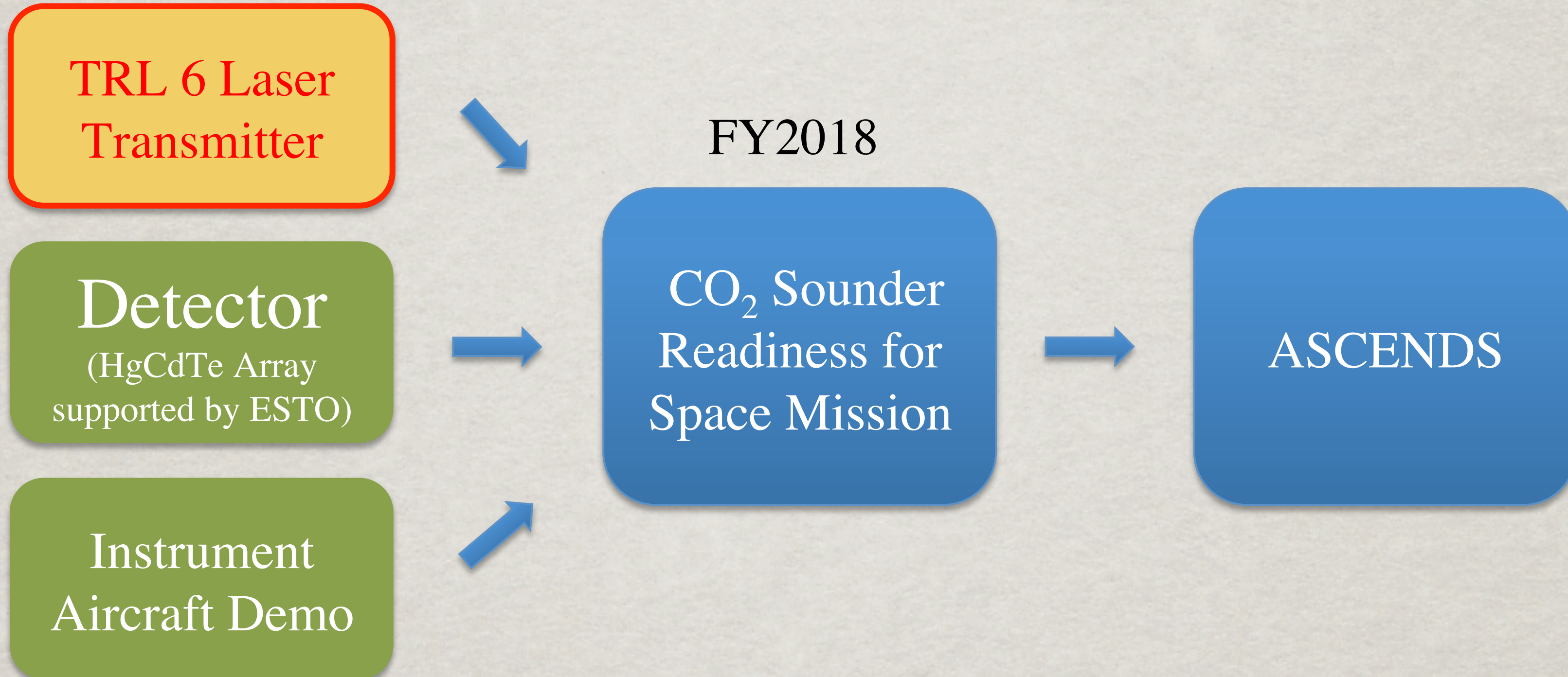
***Random error*: ~ 1 ppm in ~100 km along track, or**
~ 0.5 ppm in ~10 sec over deserts

***Bias:* < 0.5 ppm (< 1 part in 800)**

Lower errors provide more benefit for flux est's.

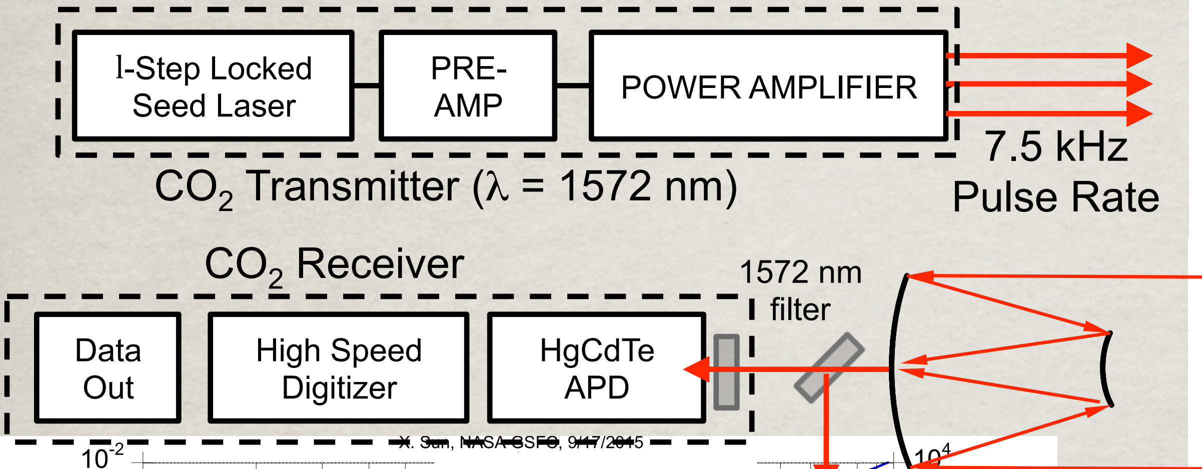
Space Laser Transmitter (TRL 6) Roadmap

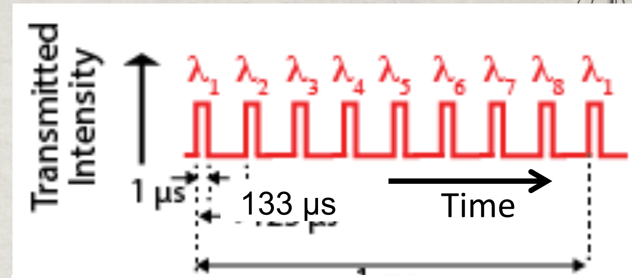
FY2015-17

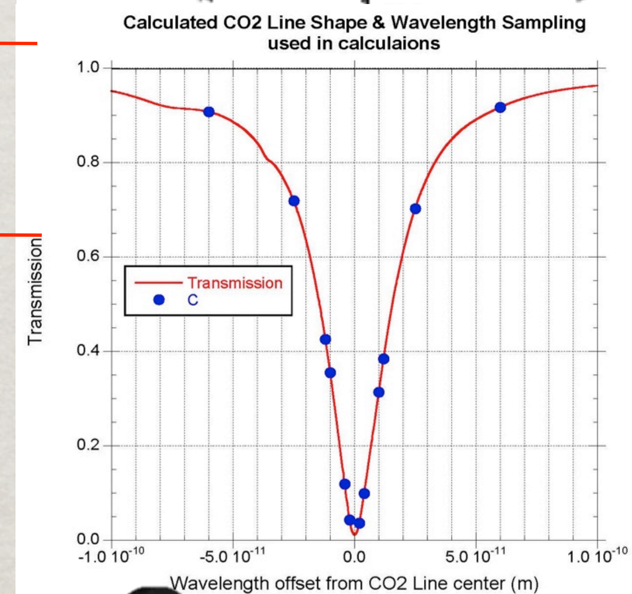


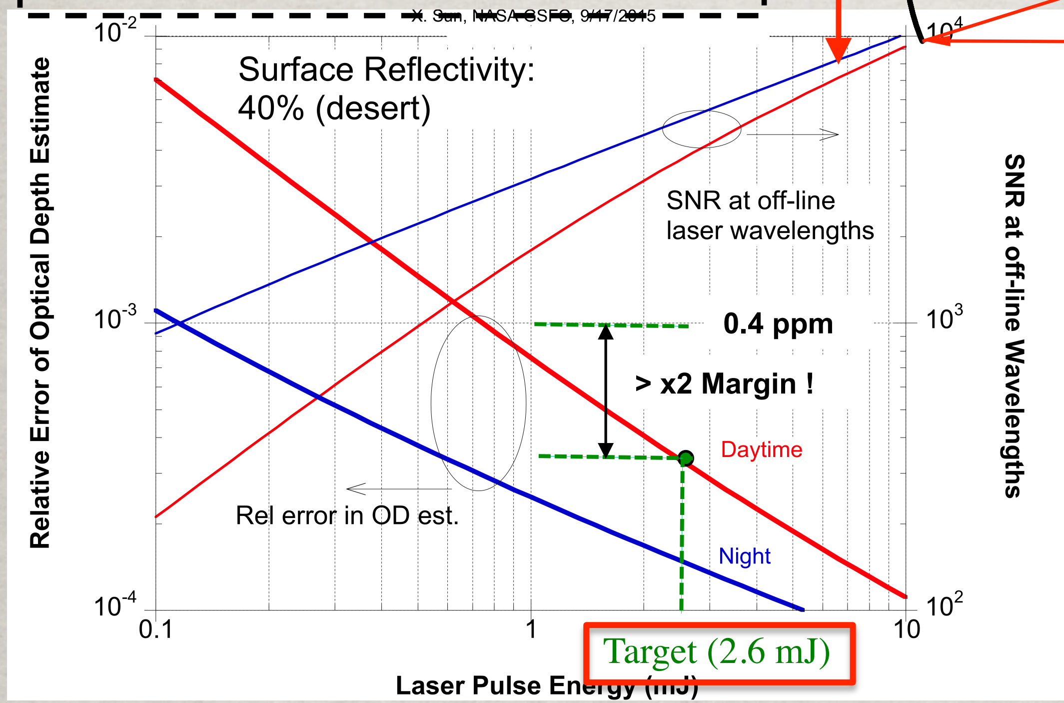
- Previous work has demonstrated most key elements needed for ASCENDS
- The main obstacle remaining for a CO_2 Sounder-based mission is the laser TRL
- A CO_2 precursor mission could be an intermediate step, as a science and technology demonstration (eg. for Earth Venture, or similar)
- **This program will increase laser TRL to 6 for flight opportunities in 2017 & beyond**
- This high peak power fiber laser also serves as a pathfinder for other space remote sensing applications

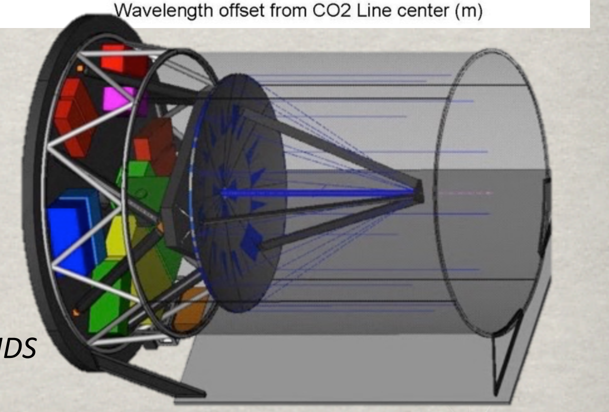
Scaling CO_2 Sounder Lidar to Space











Ref: J. Abshire, et. al., "Progress in developing the CO2 sounder Lidar as a candidate for the ASCENDS Mission," presented at SPIE Optical Engineering and Applications, San Diego, CA, August 2015.

Laser Requirements

GSFC

Performance Parameter	Laser Transmitter
Center Wavelength	Nominally centered at 1572.335 nm
Linewidth (each wavelength channel)	≤ 100 MHz (TBR)
Pulse repetition frequency	7.5 KHz
Pulse Width	1-1.5 μs
Pulse Energy	>3.2 mJ/pulse (goal); >2.6 mJ/pulse (operating, 18% derating)
PER [TBR]	20 dB (TBR)
Wall-plug Efficiency	> 6%

Performance Parameter	Laser Transmitter
Center Wavelength	**Nominally centered at 1572.335 nm**
Beam quality	M^2 <1.3 (TBR)
PER [TBR]	**20 dB (TBR)**
Environmental	Launch to ISS (TBR)
Wall-plug Efficiency	> 6%

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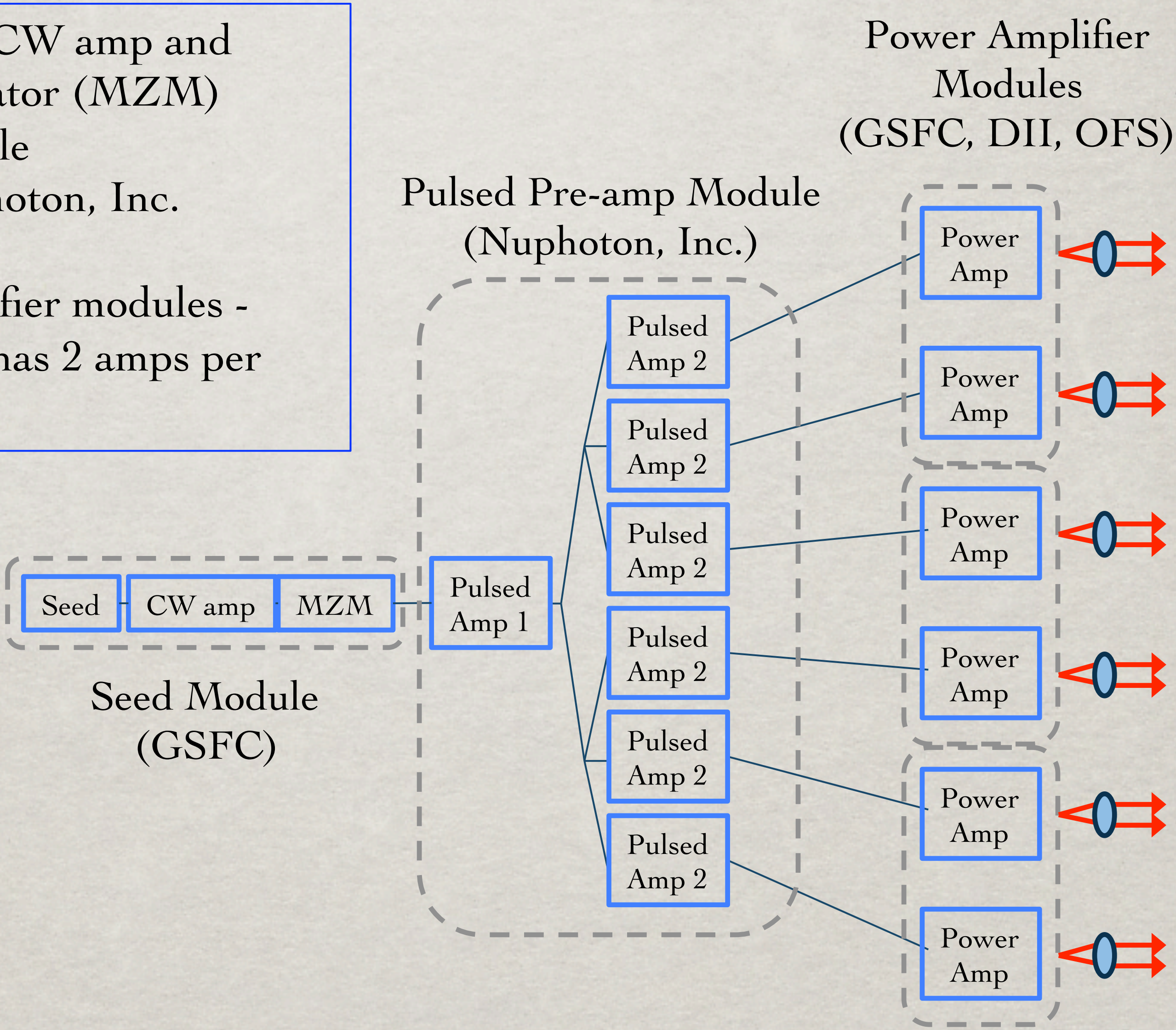
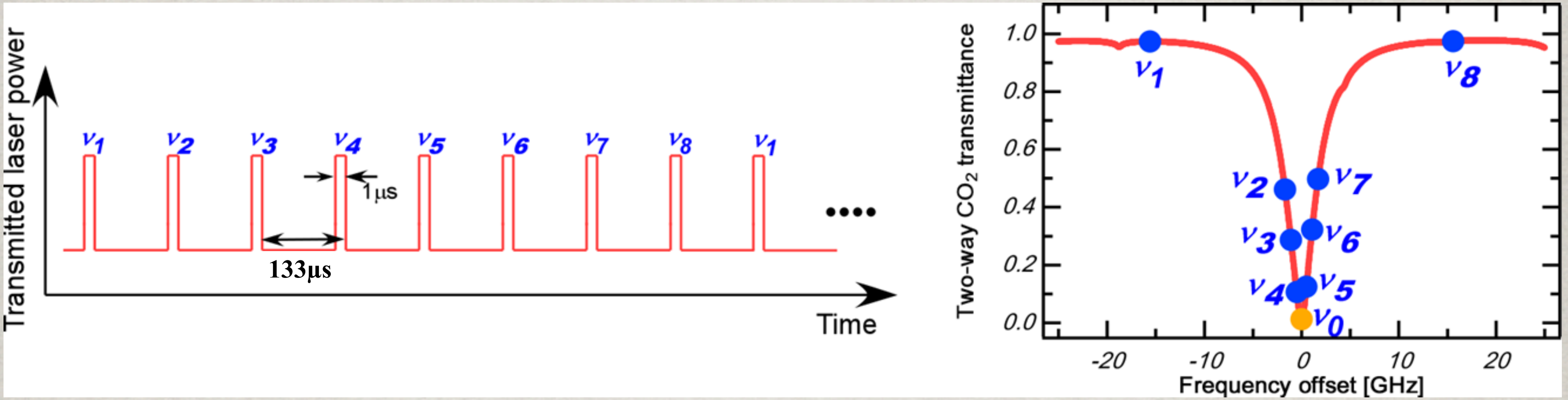
Architecture Overview

- Seed Module includes CW amp and Mach-Zehnder Modulator (MZM)
- Pulsed Pre-Amp Module
  - being built by Nuphoton, Inc.
- Power Amplifier
  - Design uses 3 amplifier modules - Packaging concept has 2 amps per module



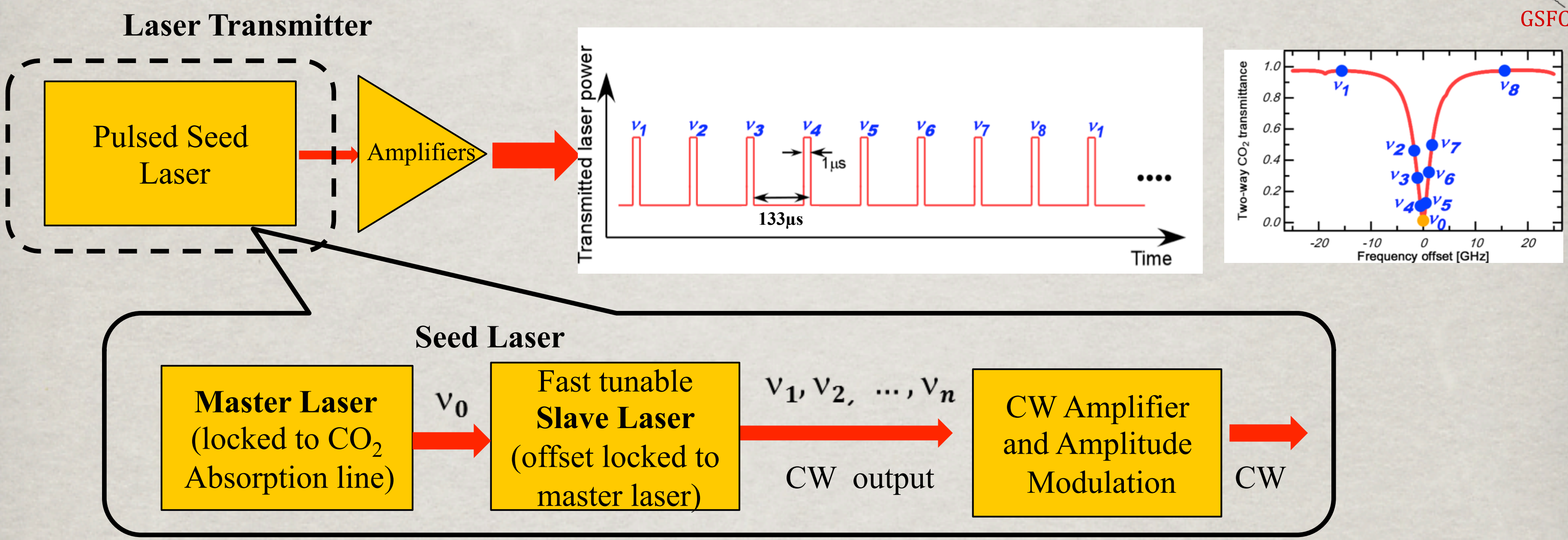
Seed Laser Module

Top-Level Function



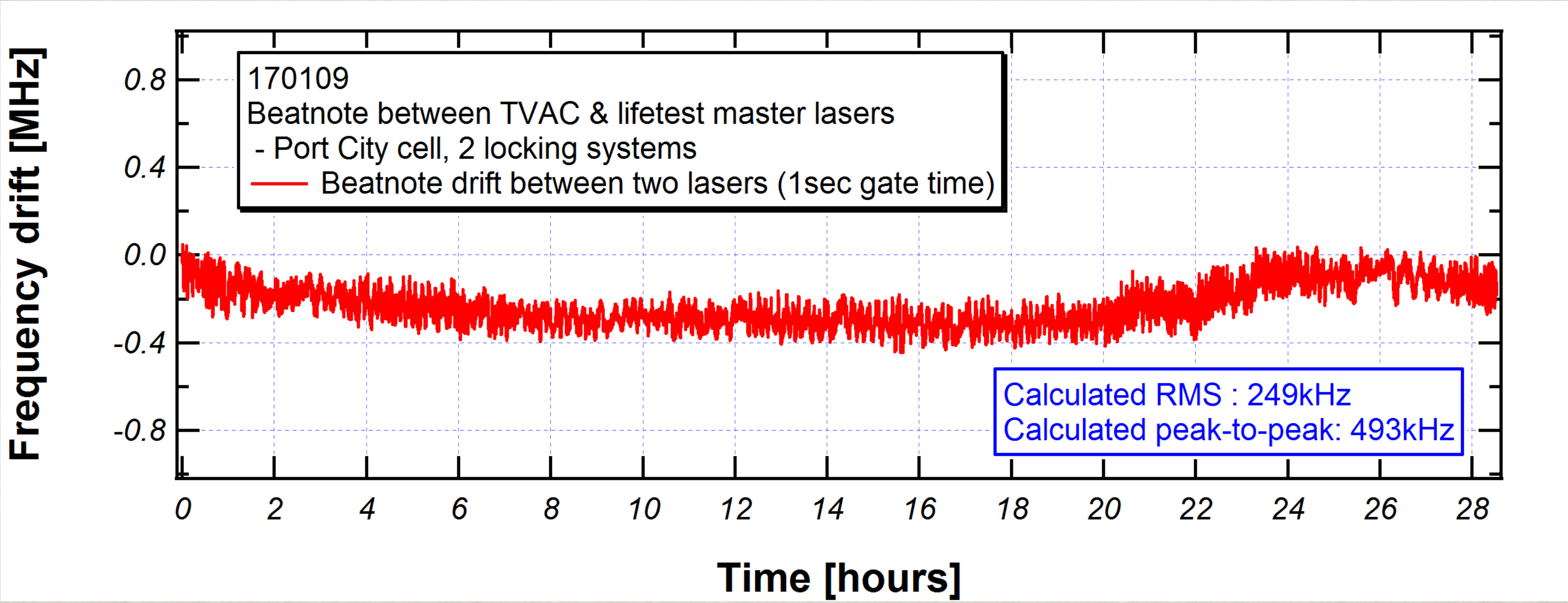
- Seed-laser provides wavelength-stepped CW laser output.
- Modulation module carves CW laser into pulses, and (optionally) broaden the laser line-shape to suppress the SBS for high peak power.
- Laser power amplifiers boost the laser pulse energy.
- The laser frequency fluctuation causes a variation in measured transmittance, hence uncertainty in the retrieval => laser frequency must be stabilized.

SEED LASER OVERVIEW



- The DFB master laser is locked to CO_2 reference cell.
- A single DS-DBR slave laser is dynamically offset-locked to the master DFB laser using an optical phase-locked loop (OPLL).
- The demonstrated laser frequency noise suppression (to < 0.2 MHz), tuning speed (< 40 μs) and tuning range (~32 GHz) **satisfies ASCENDS requirements**.
- Pulse shaping will compensate for distortions by Pre-Amp and Power Amp modules. Desire "flat top" output pulses.
- Capability to perform pulse-shaping through use of high-speed DAC currently in development

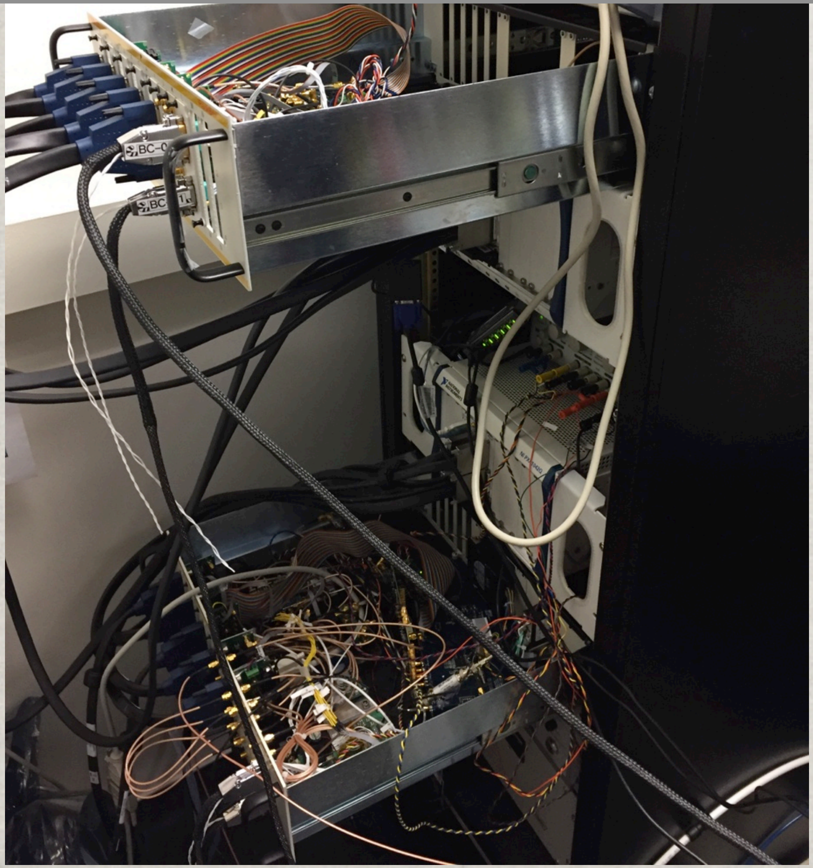
Frequency Drift of Master Laser



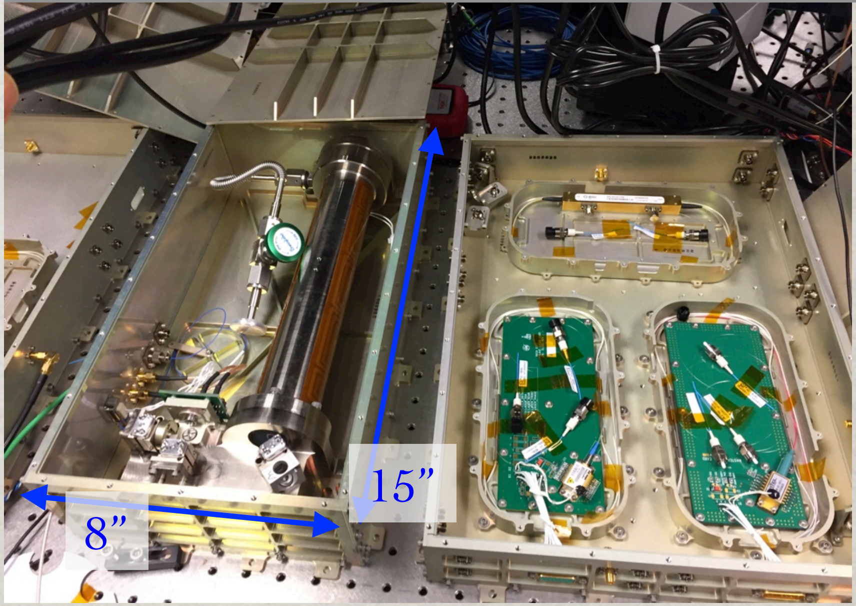
Less than 1 MHz absolute drift between two independently locked sources over a 1-day test

Overall progress in seed laser development

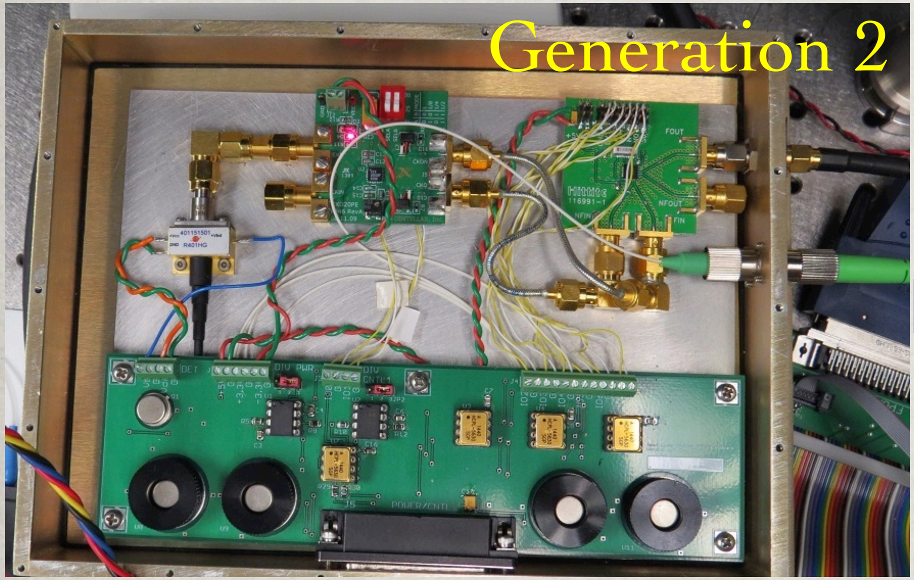
- Seed laser wavelength-locking / driver electronics have been assembled, being tested for both TVAC-test unit and the life-test unit.

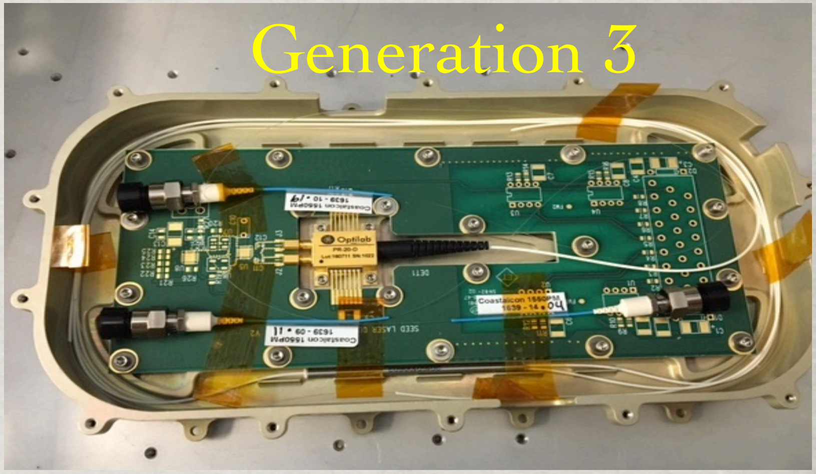


- Master Laser, Slave Laser, and CW Amplifier Pump Laser cards and the CO_2 cells all assembled and integrated into the Seed Laser box (for both TVAC unit and Life-Test unit).



Slave Laser Detector/Divider Box Improvements



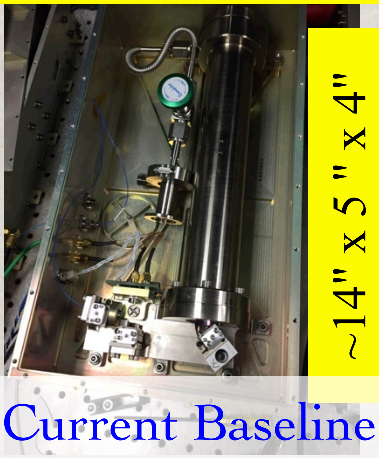


- Redesigned and built improved 20GHz optical detector/frequency divider box.
- New detector is more robust, has a simpler power scheme and contains a limiting amp
- Eliminates 20GHz cable between detector and electronics
- All components mounted on a signal PCB - fewer wires and higher signal quality
- Box also includes fiber coupler

CO_2 REFERENCE CELL OPTIONS

GSFC

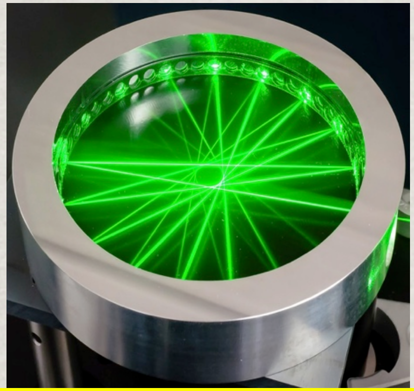
New 10 m CO_2 cell



~14" x 5 " x 4"

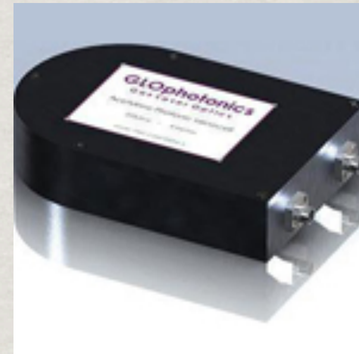
Current Baseline

Hockey puck cell (IRsweep)

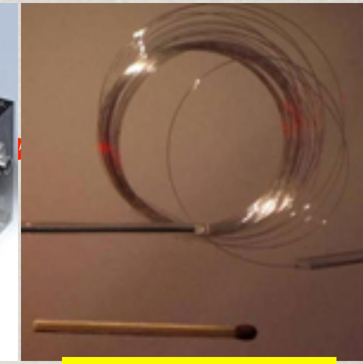


6" O.D. x 1.2" H (10m cell)

Gas-filled HC-PCF cell



2.5" x 2" x 0.5"

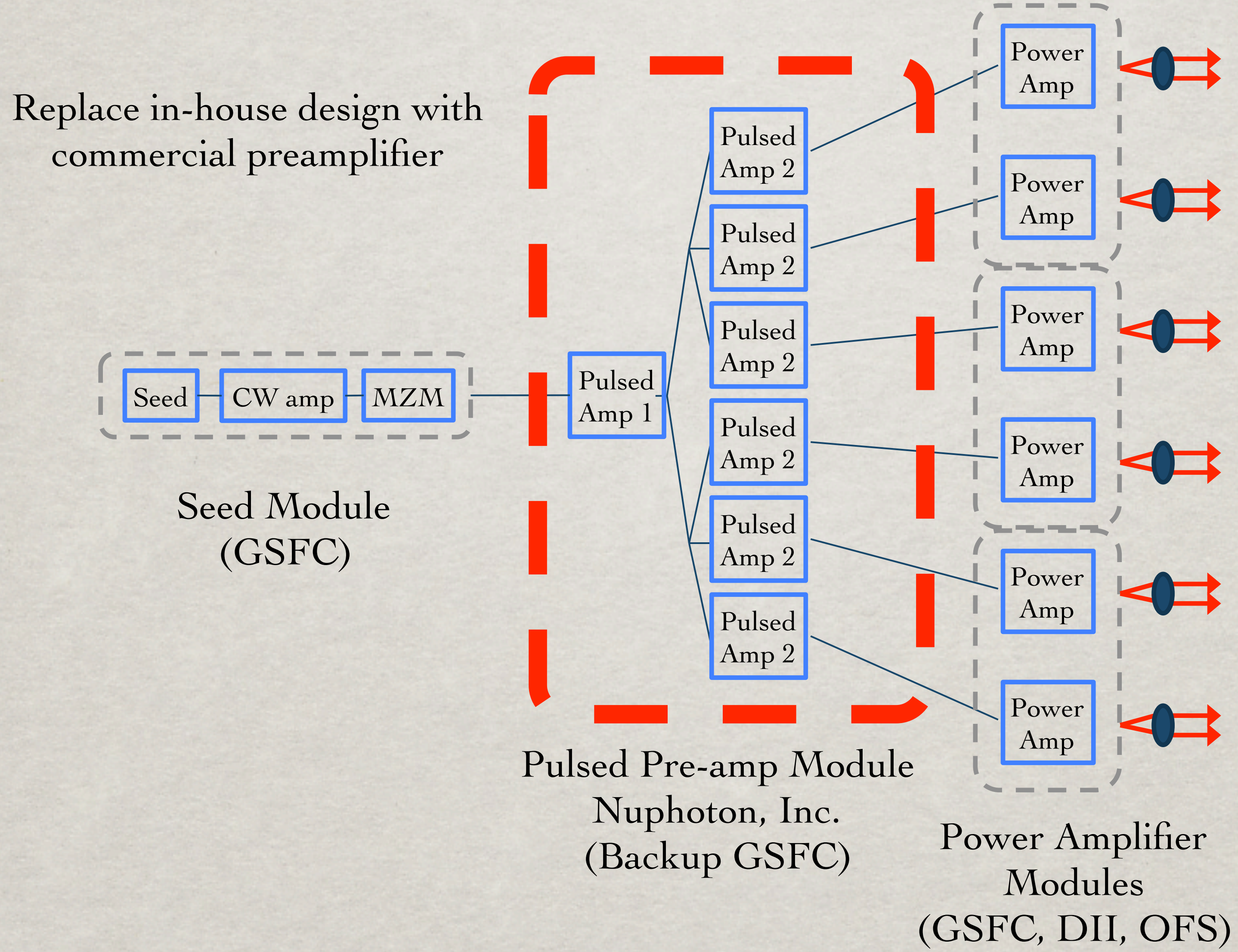


~2" Dia coil

- **Base line:** 10 meter Herriott cell made by Port City Instruments (received & tested) **-low risk**.
- **Investigating options** to replace the baseline Herriott CO_2 cell, to **reduce the cell mass/size and instability**.
- Option 1: compact 'hockey puck' cell from IRsweep - more desirable than the bulky Herriott cell. Received 4m path length cell. IRsweep is developing 10m version.
- Option 2: a gas-filled hollow-core photonic-crystal fiber (HC-PCF) CO_2 cell - much smaller, lighter, and potentially more stable due to the fiber wave-guiding
  - Our previous work has solved all other problems with the HC-PCF gas cells except unwanted spectral distortions stemming from the unwanted modes in the HC-PCF.
  - Last problem solved by others -- Stable locking has recently been demonstrated at 2.05um by P. G. Westergaard et. al. using a new HC-PCF for the CO2 gas cell

Pulsed Pre-Amplifier Module

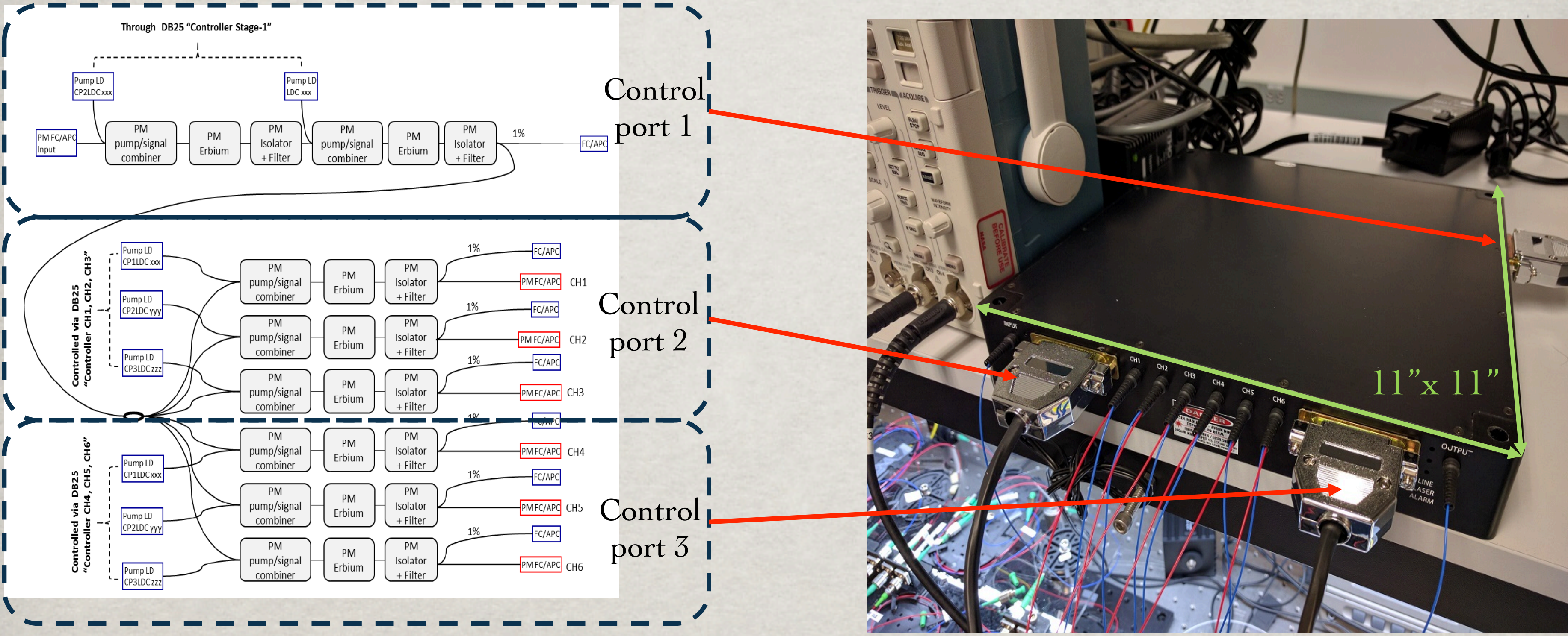
Architecture



Laser - Preamp - Split 6-ways to seed 6-Power Amps

Nuphoton Pre-Amp Module: Basic Operation-control

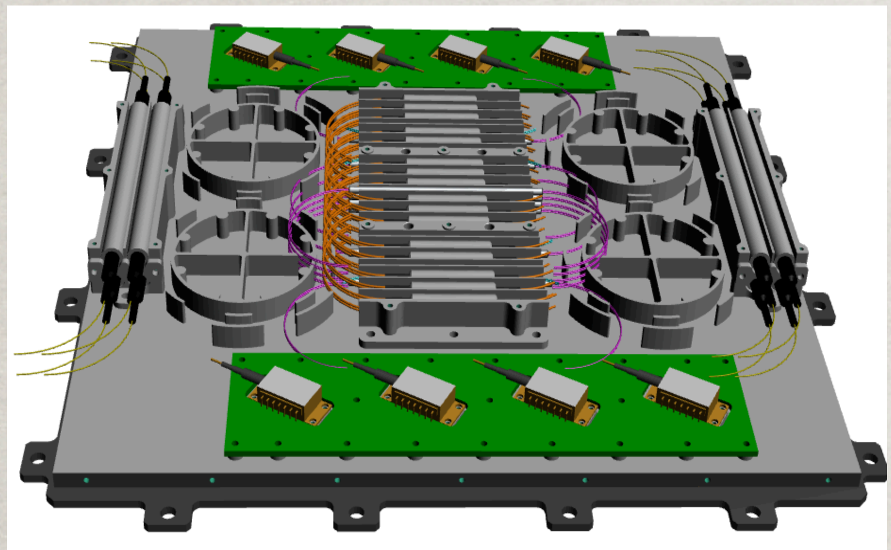
Nuphoton pre-amp module delivered and tested

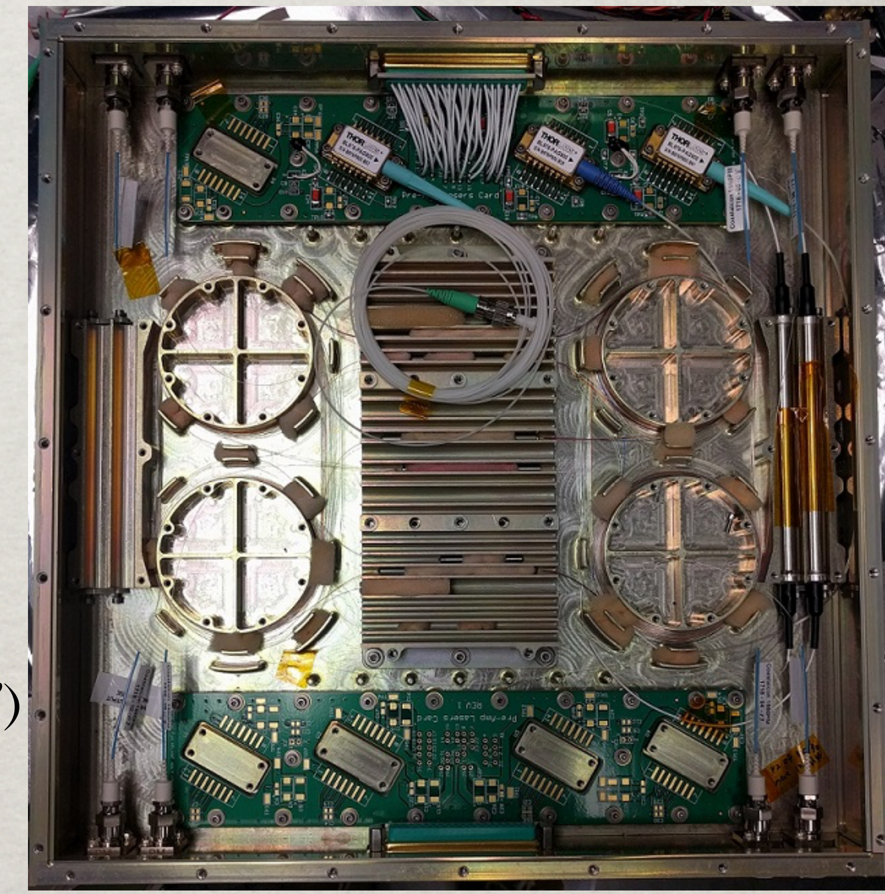


- ❑ The unit has 1 input and 13 outputs (including 7 monitor ports)
- ❑ Each output provides >5 µJ pulse energy
- ❑ OFS requires 2.5 µJ for the power amplifier
- ❑ Three serial interface for controlling different sections with hyper-terminal
- ❑ **Module meets all optical performance requirements**
- ❑ **Worked with vendor to use vacuum compatible components**

GSFC Pre-amp Design

- ➢ Preamp housing/enclosure design
- ➢ Components ordering / receiving (two vendors)
- ➢ Electronic design and assembling

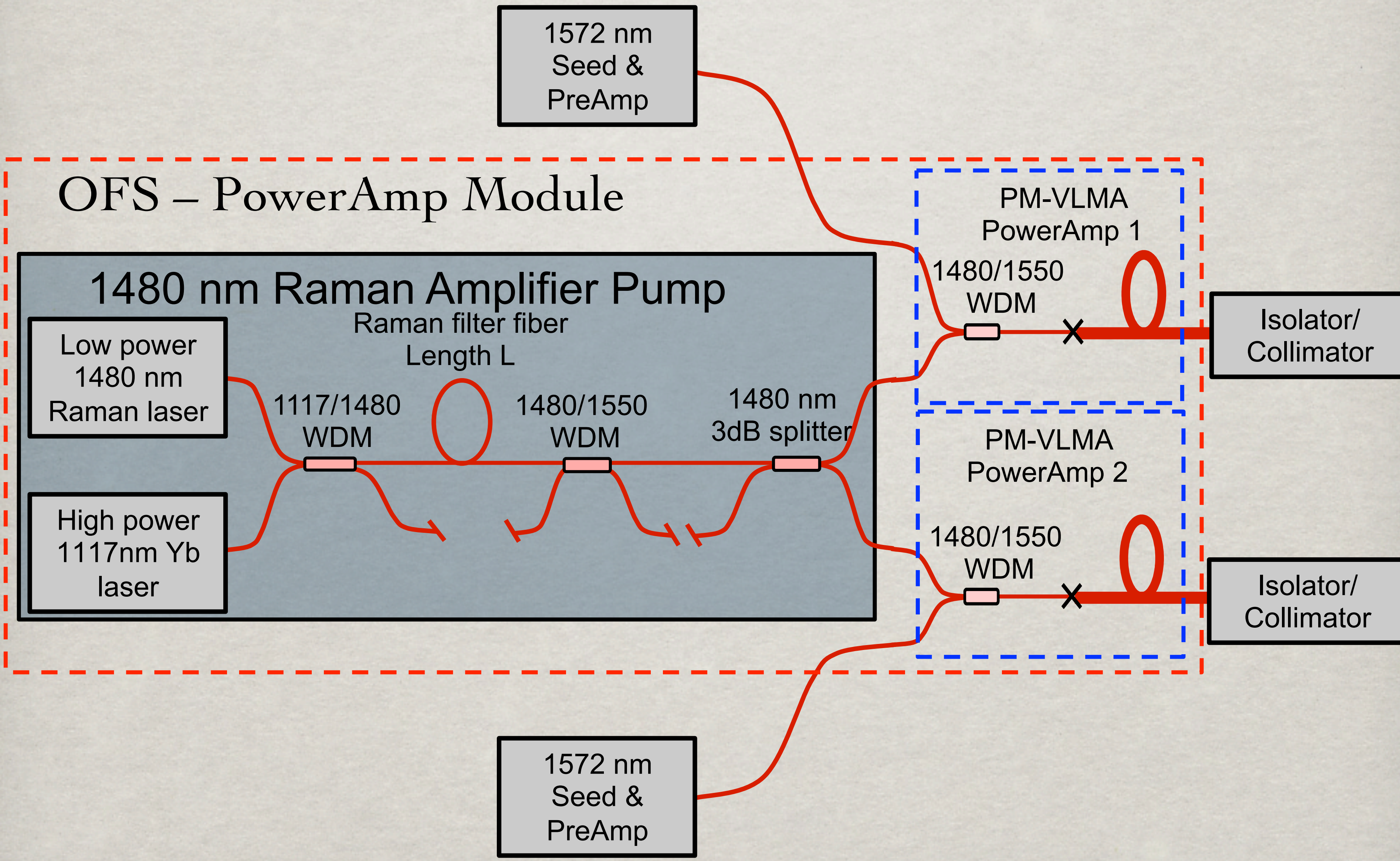




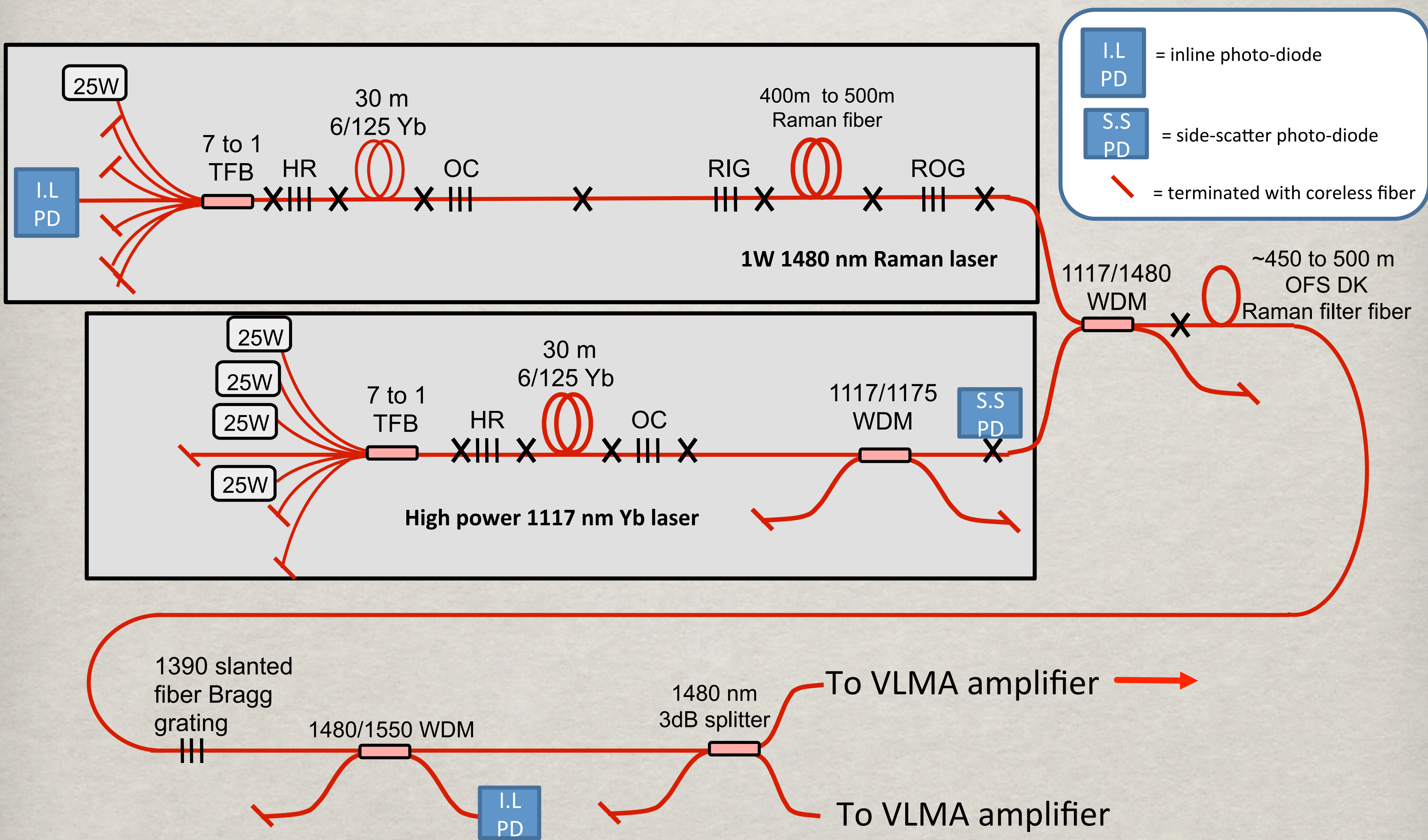
- ✓ 2-Stage EDFA
- ✓ Single layer structure (~12" x 12" x 2")
- ✓ Redundant holders for passive optical components
- ✓ Multiple routing path for fibers.

Power Amplifier Module

Power Amplifier Module Architecture

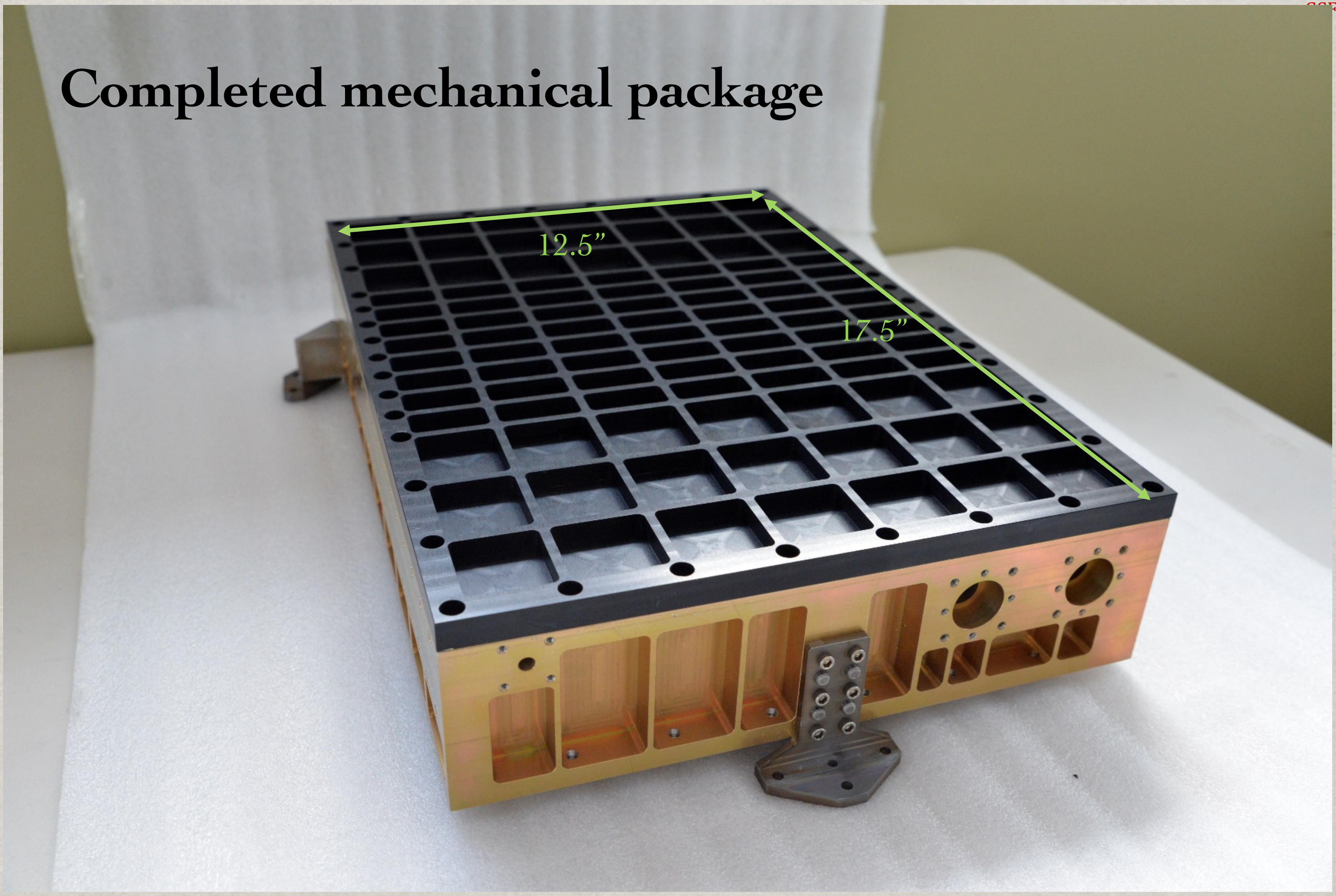


30W Raman Amplifier 1480nm Pump: Detailed schematic



Power Amplifier Housing

Completed mechanical package



Power amplifier interior

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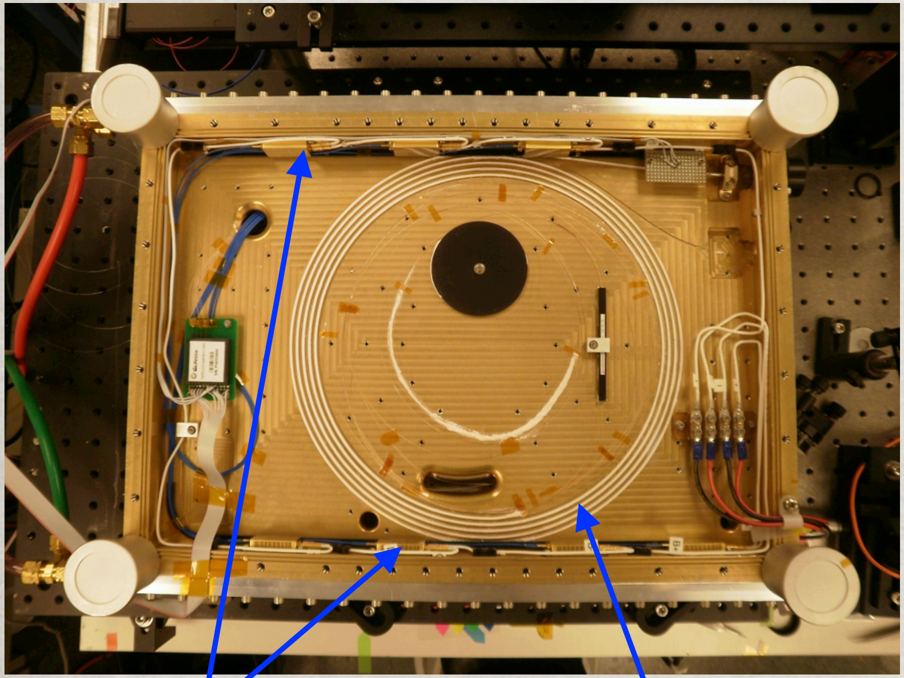
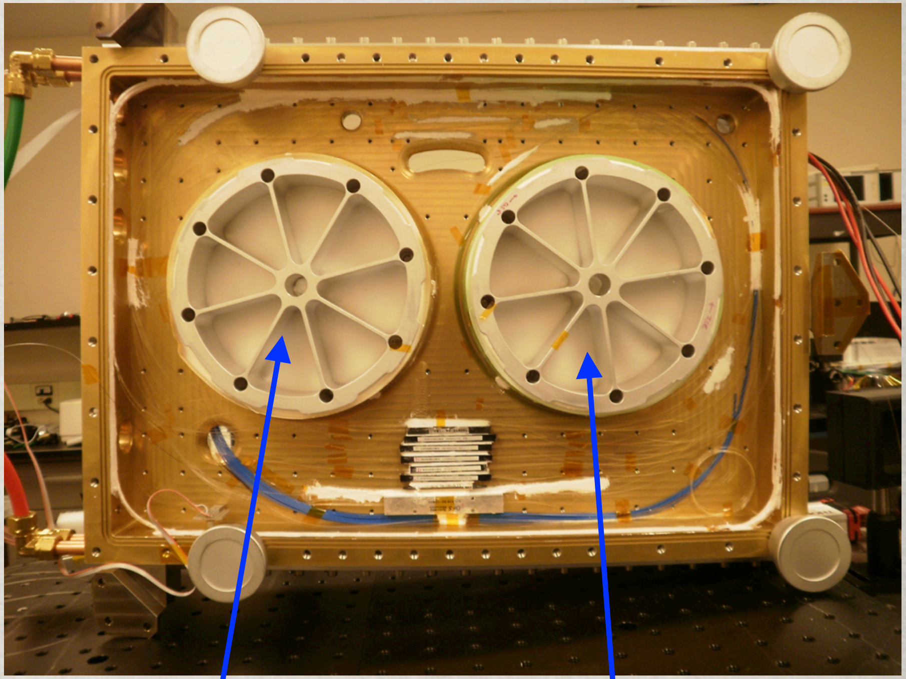
View of PM-VLMA Side of Baseplate



View of Raman Fiber Laser Side of Baseplate



Pump diodes for Raman Fiber Laser

PM-VLMA Fiber

Raman Fiber Laser

Raman Fiber Amplifier

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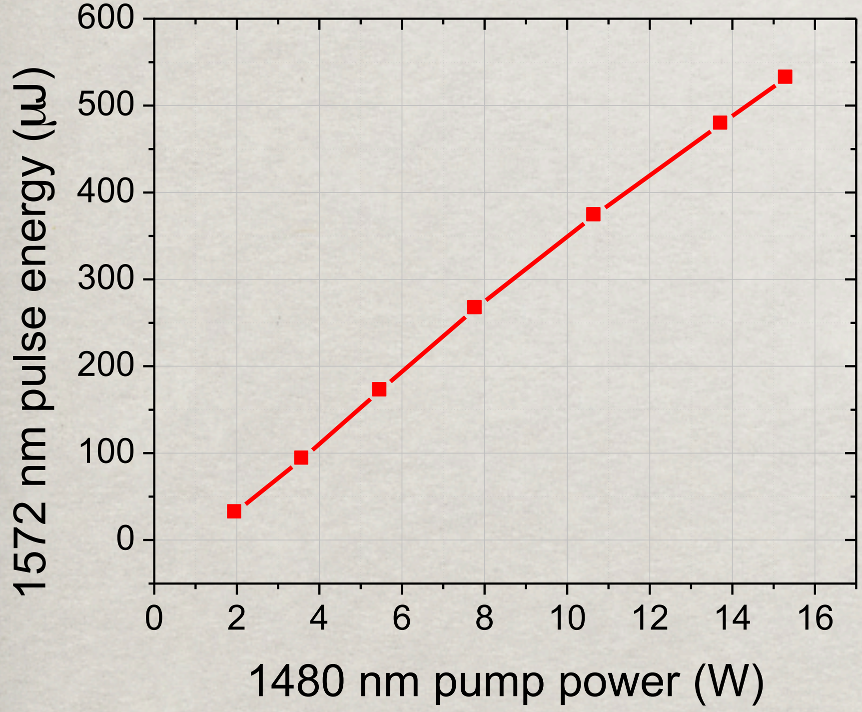
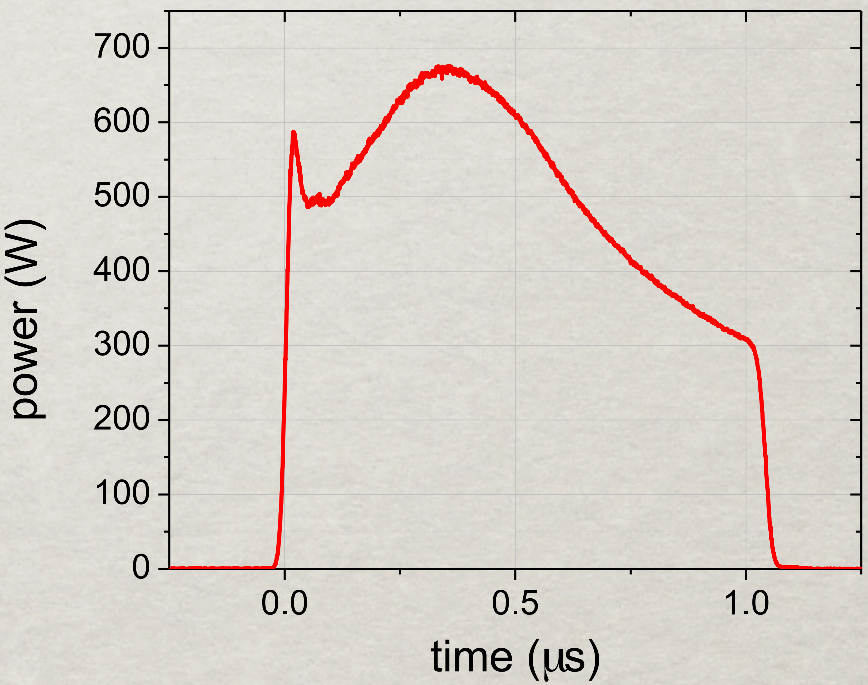
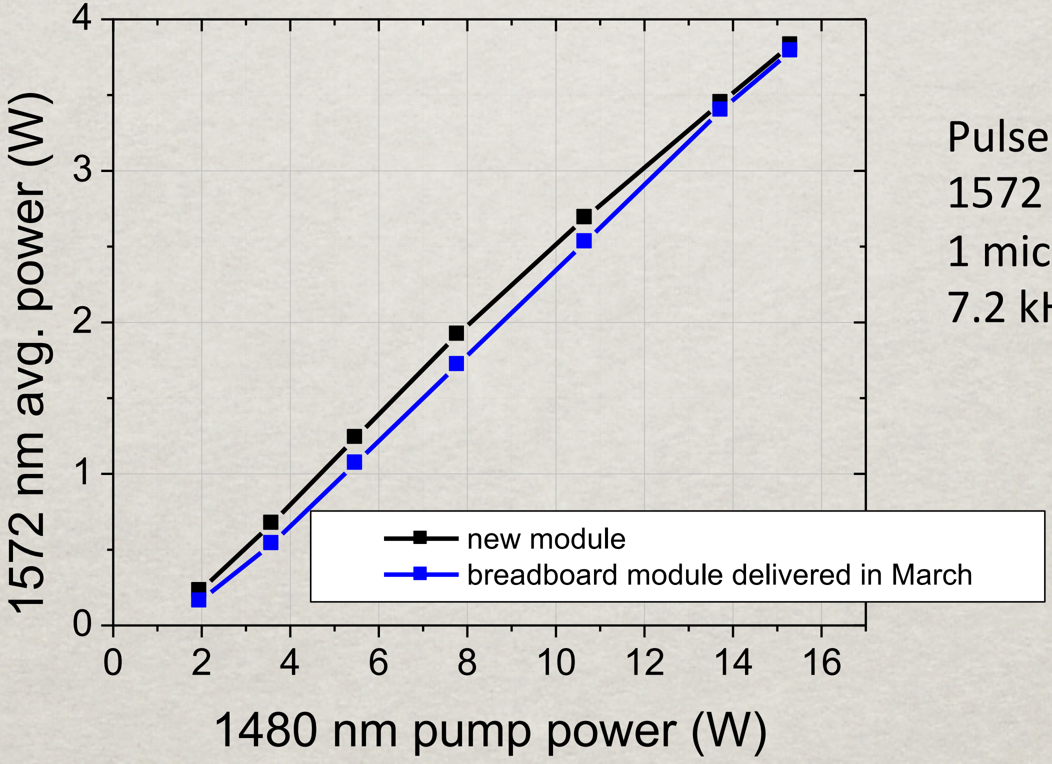
PM VLMA amplifier
Pulse energy and peak power





Pulse energy : 531 μJ
Peak power : 675 W

PM VLMA amplifier Comparison with breadboard module delivered in March

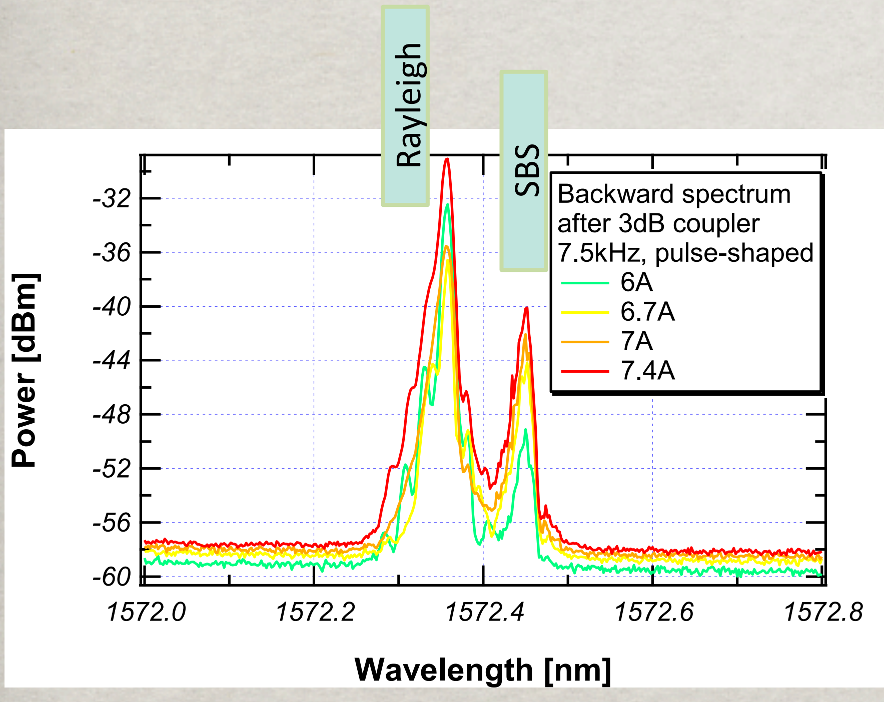


Pulsed operation
1572 nm
1 microsecond pulses
7.2 kHz

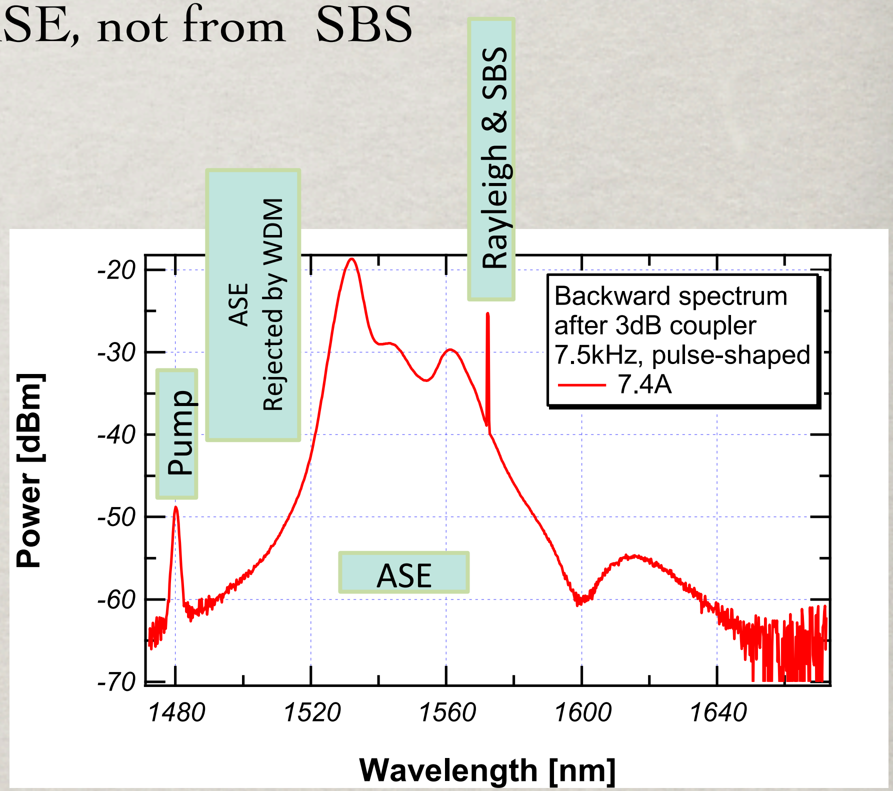
- Output power is slightly higher at low pump power in new module
- Could be due to differences in end-cap type

Backward Spectrum
in high energy regime

- SBS peak was always kept below Rayleigh peak conservatively.
- Most of the backward power is from ASE, not from SBS



Narrow-band view



Wide-band view

RAMAN-PUMPED VLMA EDFA OUTPUT PULSE ENERGY

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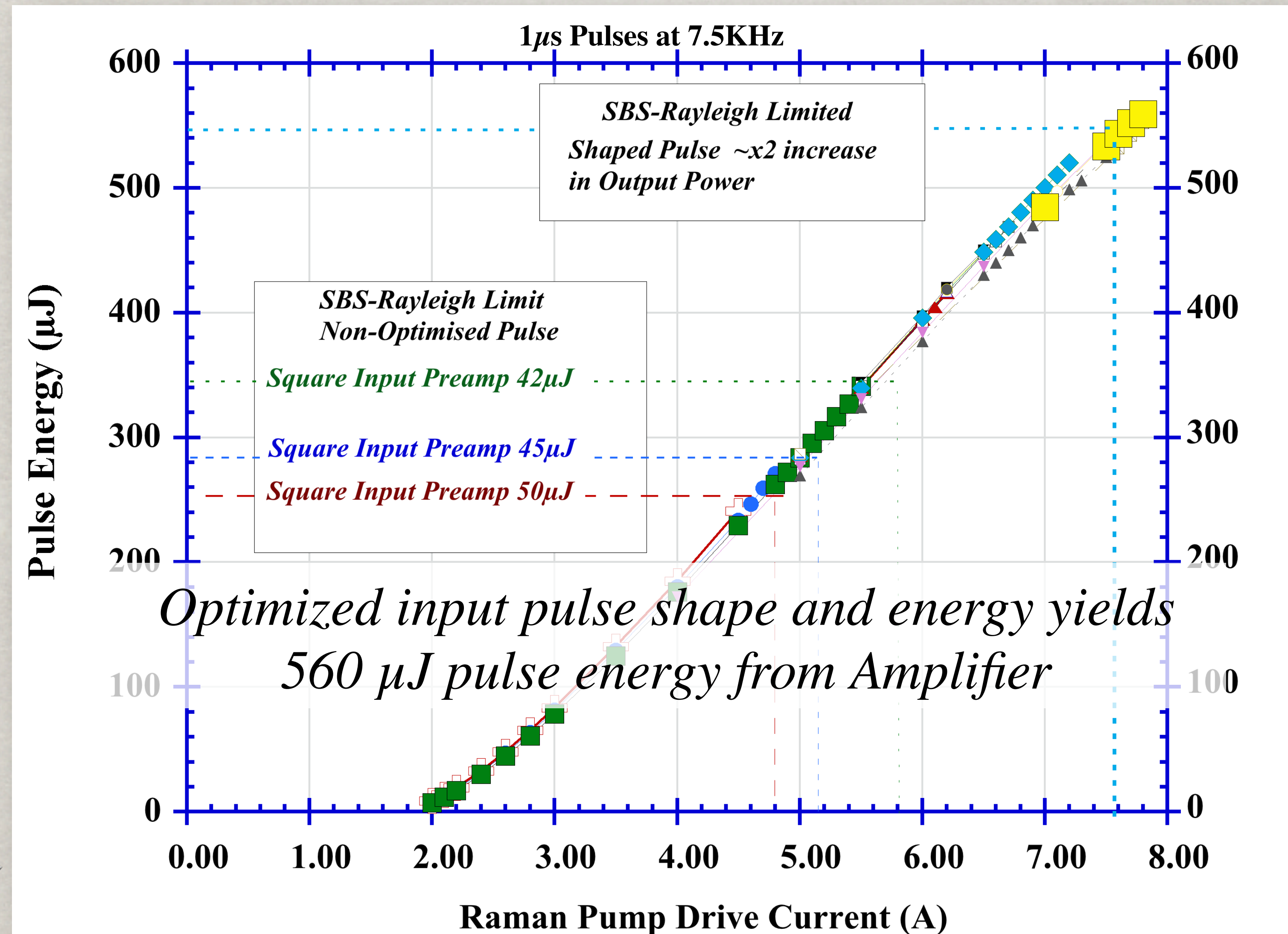

Optimized input pulse shape and energy yields 560 μJ pulse energy from Amplifier

ofs
A Furukawa Company

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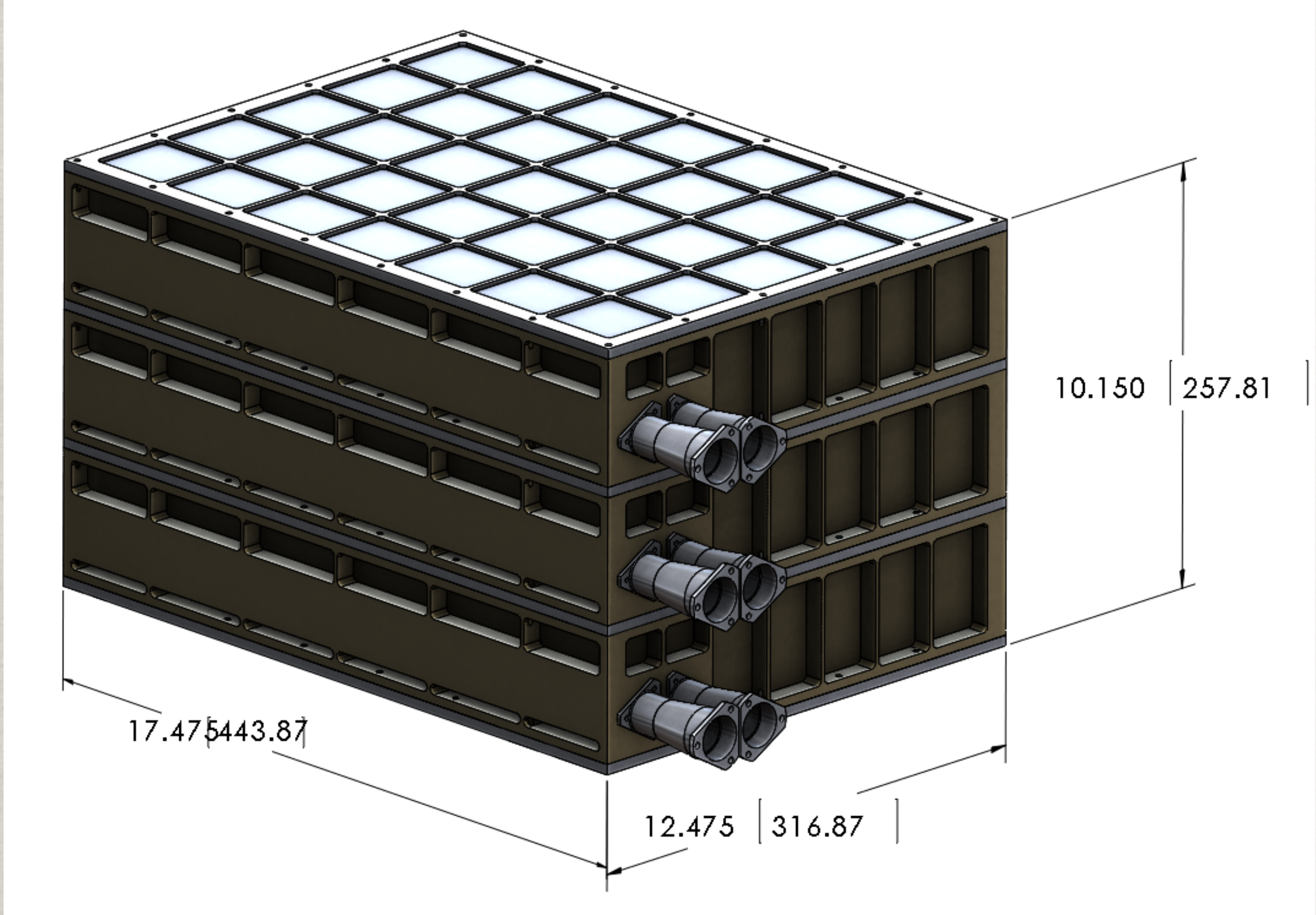
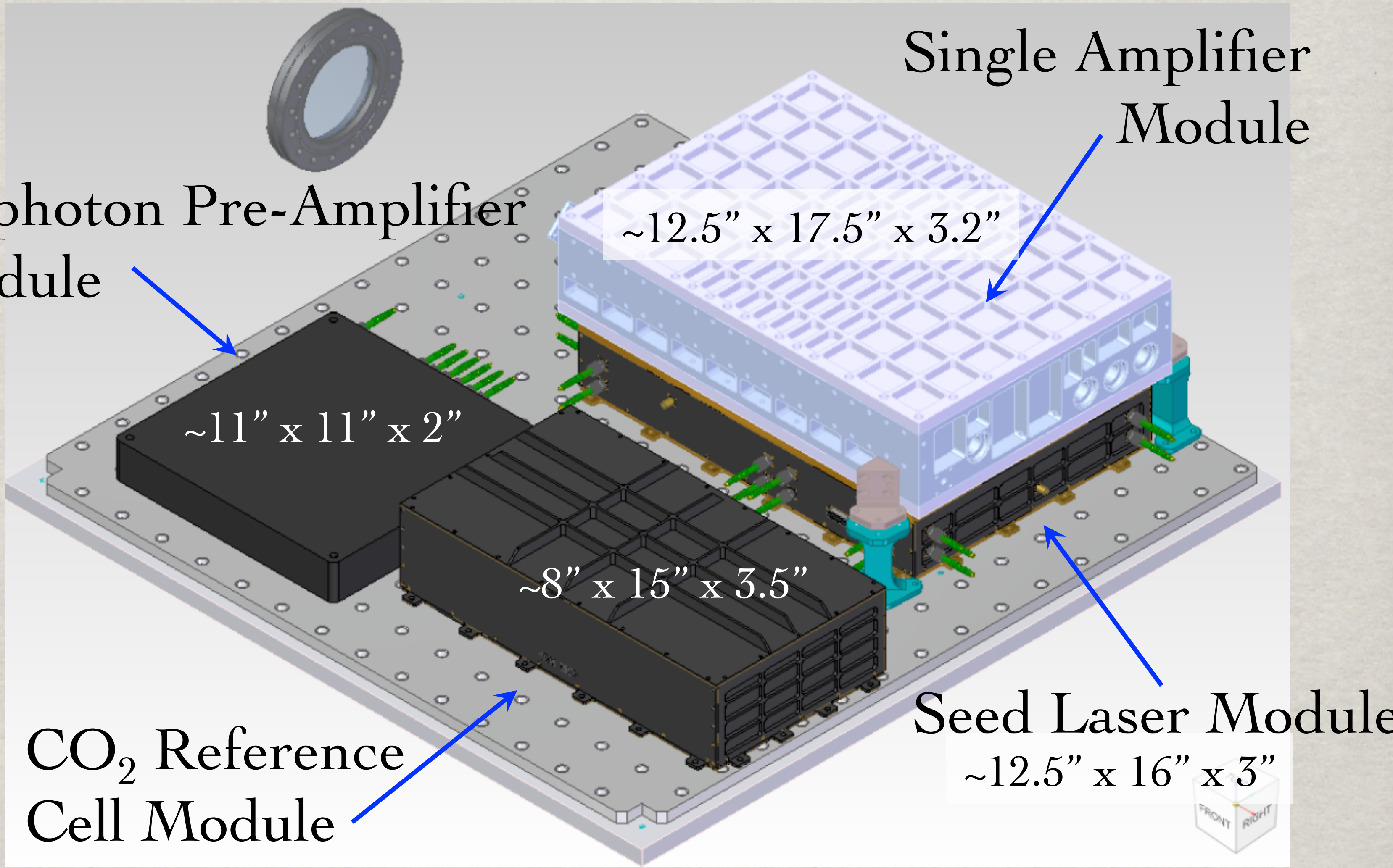
Power Amplifier Build Conclusions

- Raman amplifier and PM VLMA amplifier built, characterized, and ready for integration into mechanical hardware designed by Design Interfaces.
- **Raman laser** –
  - 30 W output power at 1480 nm (after slanted FBG and 1480/1550 WDM) for 49.2 W diode power
  - O-O efficiency = 61%
  - Sufficient for pumping two PM VLMA amplifiers
- **PM VLMA amplifier**
  - 531 μJ, 675 W peak power, single frequency microsecond pulses at 7.2 kHz rep rate.
  - 1480 power required for 500 μJ pulses = 14.2 W
  - O-O efficiency = 25%

3 Stacked Modules

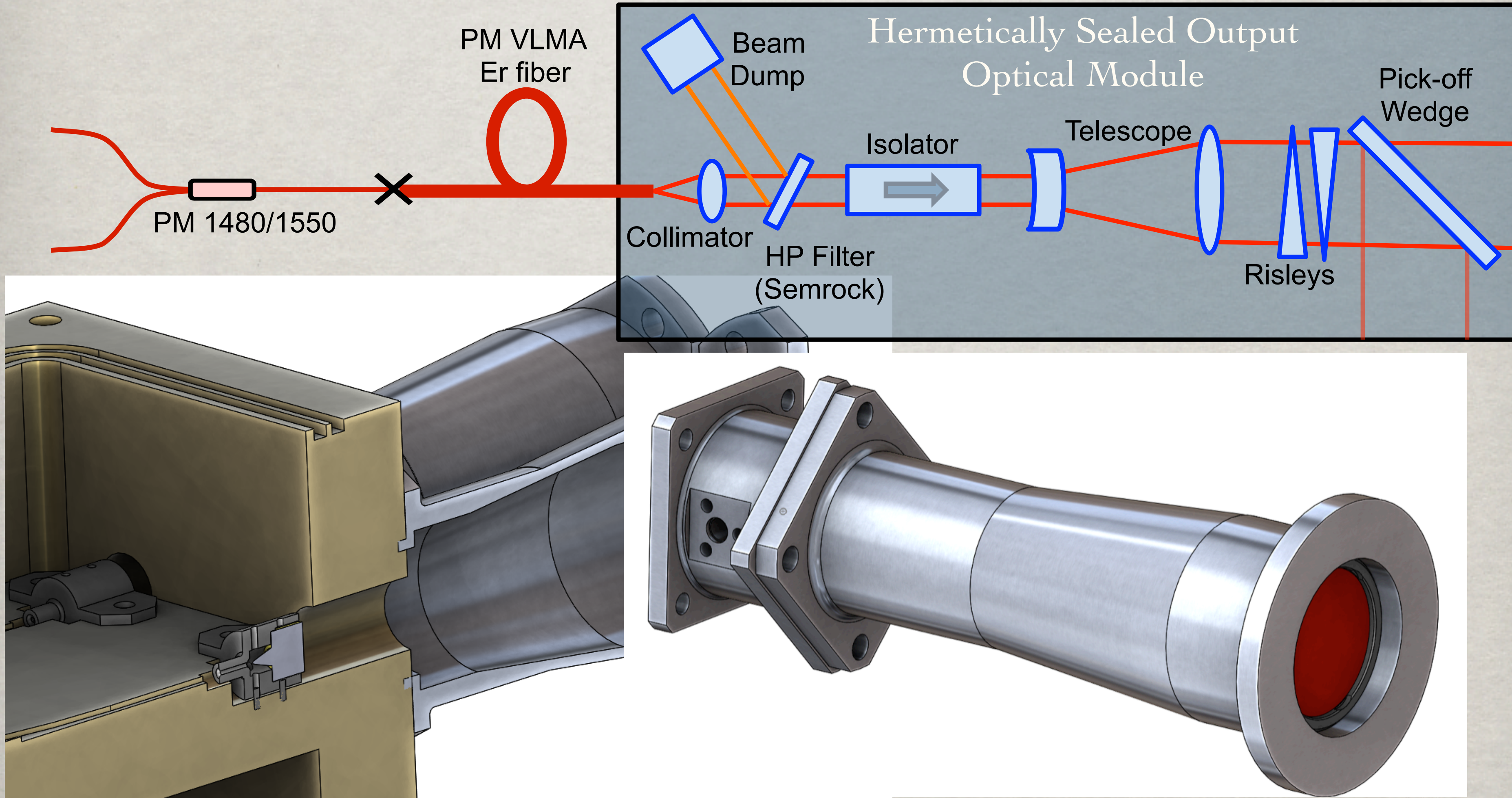


MOPA (with one Amplifier) for TRL6 Qualification Test



Output Optical Module

- PM-VLMA fiber amplifier terminated with an end-cap
- Hermetically sealed to minimize contamination
- Co-boresighted to allow far field summing of output power



Conclusions

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- We are working toward improving the TRL of the laser transmitter for CO_2 lidar to 6
- We have completed mechanical and thermal design and analysis.
- A power amplifier prototype meeting all optical performance requirements with margin was built, delivered, characterized and demonstrated in early 2017
- An engineering unit is being built and environmental testing will be conducted in summer of 2017
- Full power demonstration with 6 amplifier channels in Fall of 2017
- A copy of this OFS VLMA amplifier (@ 1550 nm) was built for the Laser Communications Relay Demonstration (LCRD) mission's ground station – this amplifier out-performs the best available commercial product.

Acknowledgements

GSFC

Partners:

NASA/GSFC - Greenbelt, MD

OFS Laboratories – Somerset, NJ

Nuphoton Technologies - Murrieta, CA

Design Interface Incorporated - Finksburg, MD

SSAI – Lanham, MD

Sponsors:

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NASA Goddard IRAD program

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Backup Charts

REQUIREMENTS (1 OF 2)

Performance Parameter	Seed Module CW Diode Source	Pre-Amplifier Module Modulator + Pre-Amps + Splitters + filters (single channel)	Single Power Amplifier Module	6-Channel Combined Transmitter
Center Wavelength	Centered at 1572.335 nm (can be moved to adjacent lines)			
Wavelength Span	200 pm from 1572.23 nm to 1572.43 nm (in 8 or 16 wavelength steps, TBR)			
Tuning speed	~100 μs/step	NA	NA	NA
Linewidth (each channel)	**<50MHz (TBR)**	**<50 MHz (TBD)**	**≤ 50 MHz**	**≤ 50 MHz**
EDFA noise figure <5dB	NA	<5dB	<5dB	NA
Side-mode suppression ratio (spectral)	>30 dB	>30 dB	>30 dB	NA
Wavelength stability (each channel) fast	Locked to < 3 MHz (1μs averaging time)	NA	NA	NA
Wavelength stability (each channel) slow	Locked to <0.3 MHz (1s averaging time)	NA	NA	NA
Wavelength locking reliability	Mean time to loss of lock - 24 hrs with 1 sec. re-lock time	NA	NA	NA
Pulse repetition frequency	7.5 KHz			
Pulse period (derived)	133 μs			
Pulse Width	<1.3 μs (goal 1 μs)			
Duty Cycle	0.75 % (Derived from Pulse period & pulse width)			
Rise Time			10-25 ns goal	
Fall Time			10-25 ns goal	
Pulse shape	NA	Pre-shaped (TBD)	Flattish Top	Same
Pulse energy	NA	> 4 μJ per channel (TBD)	>600 μJ/pulse (goal) >450 μJ/pulse (operating, 18% derating)	Sum at Farfield >2.7 mJ/pulse (operating, 18% derating)
Average power (informational derived)	9 mW - CW	30 mW	3 W (goal); 2.48 W (operating)	Sum at Far Field 20 W (op)
Peak power	9 mW	(4 μJ /1 μs)*5 = 20W (assumes pulse shape factor of 5)	600W (goal) 450W (op)	3.2 KW goal 2.5 kW operating

Requirements (2 of 2)

GSFC

Performance Parameter	**Seed Module** CW Diode Source +PreAmp + Modulator	**Pulsed Pre-Amplifier Module** Pre-Amps + Splitters + filters (single channel)	**Single Power Amplifier Module**	**8-Channel Combined Transmitter**
Pulse Extinction ratio (timing)	NA	> 35 dB	> 30 dB	> 30 dB
% of power in the pulses (derived)	NA	95%	90%	90%
ASE	NA	< .05 %	<1% of average power	<1% of average power
Margin to SBS threshold	NA	> 25%	> 25%	> 25%
Pulse energy stability (short term – 1 min)	< 3%	< 3%	< 1%	< 1%
Pulse energy stability (long term – 1 hr)	< 5%	< 5%	< 5%	< 5%
Trigger (format – TTL?)	External trigger	NA	NA	NA
Optical Back reflection tolerance – i.e. isolation	~30 dB	20 dB (TBR)	20 dB (TBR)	NA
Optical back reflection	NA	~30 dB		NA
Optical Output	Fiber, SM, PM	Fiber, SM, PM	Free space, PM, ~100 μrad divergence, beam diameter/ clear aperture	Free space, PM, ~100 μrad divergence, beams co-aligned to better than ~20 μrad
Beam quality	$M^2 < 1.1$	$M^2 < 1.1$	$M^2 < 1.3$	
Mode Stability / Pointing	NA	NA	<10% of total	<10% of total
PER [TBR]	>20 dB	>17 dB	17 dB	17 dB
Environmental	TBD	TBD	TBD	TBD
Mech. Package (size, ICD)	TBD	TBD	TBD	TBD
Wall-plug Efficiency	TBD	TBD	>6% (goal)	5% goal
Communication interface	TBD	TBD	TBD	TBD
Interlocks/safeties	TBD	TBD	TBD	TBD
Reliability	1 year + testing (TBR)	1 year + testing (TBR)	1 year + testing (TBR)	1 year + testing (TBR)
% of time operational	TBD	TBD	TBD	TBD

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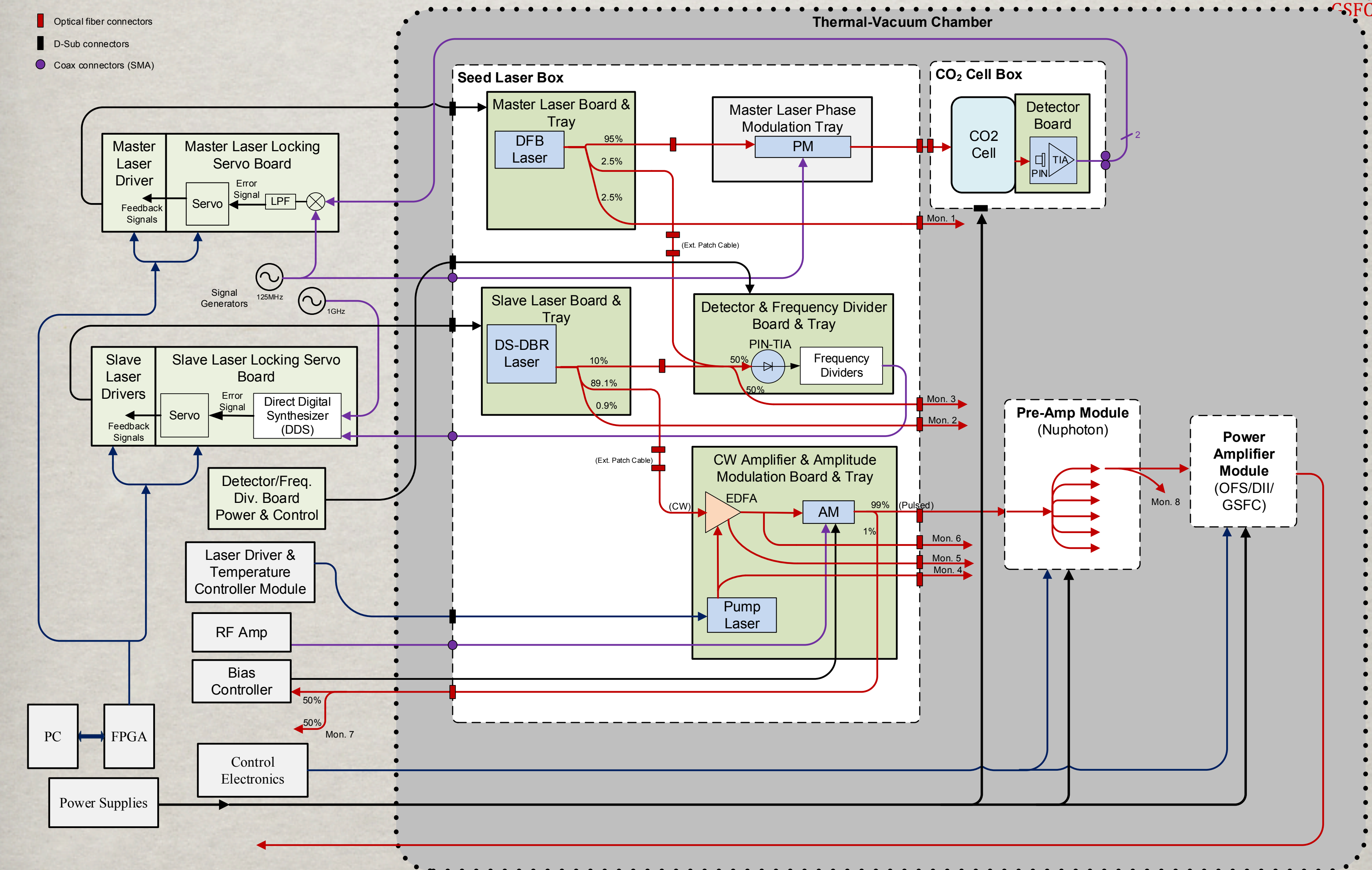
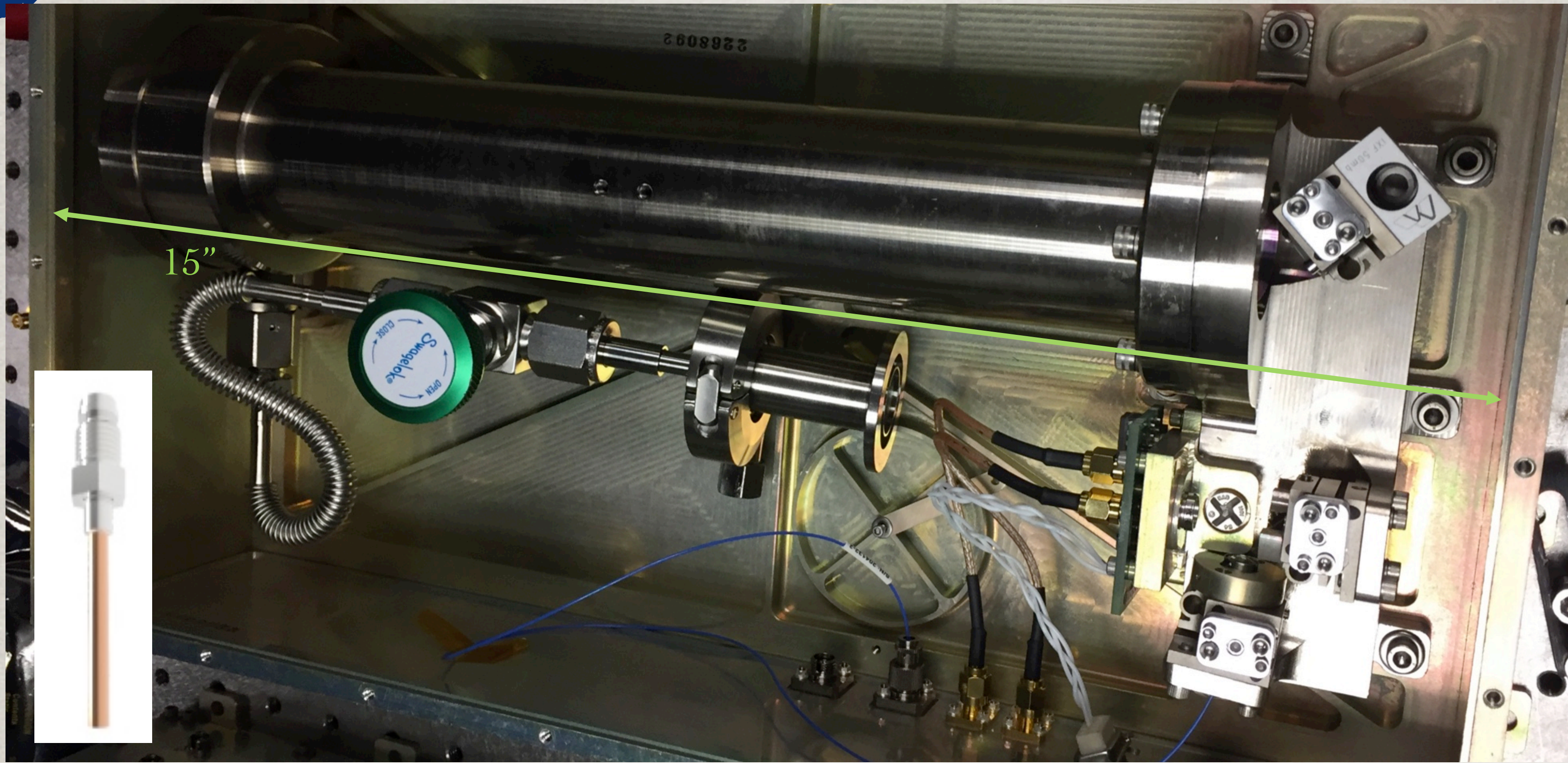
Current Environmental Testing Block Diagram



Improvements on Port City CO_2 cells



- Received and assembled two new Port City CO_2 gas cells.
- The input/output optic shelf and the end flange are now a single piece to improve stability.
- The Cell will be sealed by a pinch-off copper tube (connected to the cell via the VCR port) that will replace the gas valve shown in the picture.
- Good wavelength locking results obtained with the new CO_2 cells.

Basic Operation-average output power

Measured with reduced current (500mA) at pump 1	
Channel	**Average Power (mW)**
CH1	54
CH2	60
CH3	62
CH4	62
CH5	64
CH6	61

Data sheet from Nuphoton with default current

Channel	Average Power (mW)	Energy (uJ)
CH 1	68	6.2
CH 2	72	6.3
CH 3	72	6.3
CH 4	69	6.2
CH 5	73	6.3
CH 6	69	6.2

- ✓ Ch1 & Ch 2 output fiber was found damaged during testing.
- ✓ Energy with reduced pump 1 current at each channel is about ~5 μJ. (2.5μJ needed for OFS amp)

Preamp Design
(Nuphoton, Inc.)

We received and tested the 1st unit from Nuphoton. **Some parts used were identified as not vacuum compatible (high outgas rate):**

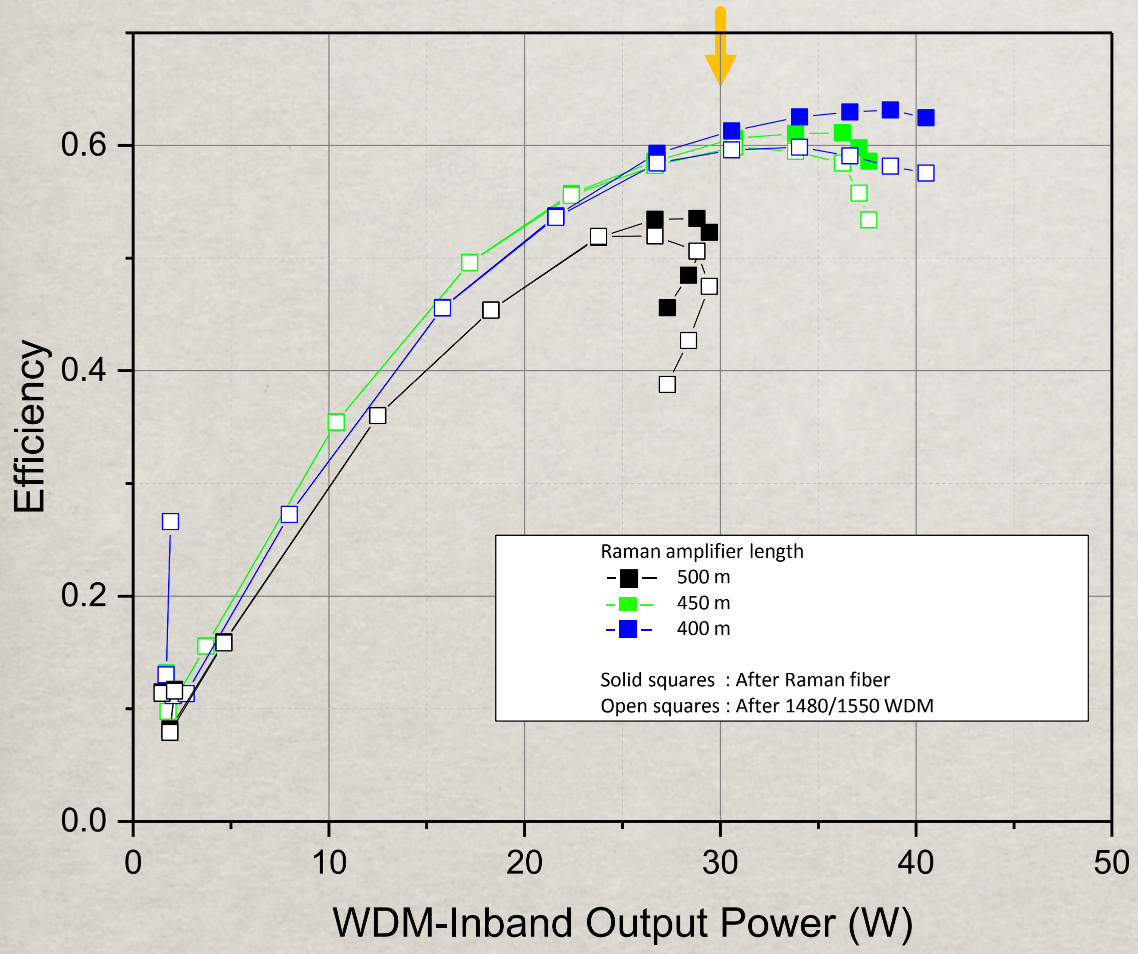
1. Electrical wires (replaced with Teflon insulated)
2. Optical protection boot (replaced with Hytrel-8068)
3. Rubber boot on passive components. (replaced with Hytrel-7246)
4. Pump diodes labels. (removed)
5. Konform coating on PCB boards (removed)

- ❑ A bakeout (pre-TVAC) was done on 12/9 to study the outgassing behavior.
- ❑ Will use the 1st unit for life test and 2nd unit for TVAC.

Raman Amplifier Fiber Length Optimization

GSFC

At ~30W output power level, efficiency is flat



When Raman amplifier is too long, nonlinear broadening leads to additional loss due to long wavelength loss of Raman filter fiber

Broadening also adds loss due to wavelength dependence of 1480/1550 pump signal WDMs.

Efficiency is optimized for ~400 m of Raman filter fiber in the Raman amplifier

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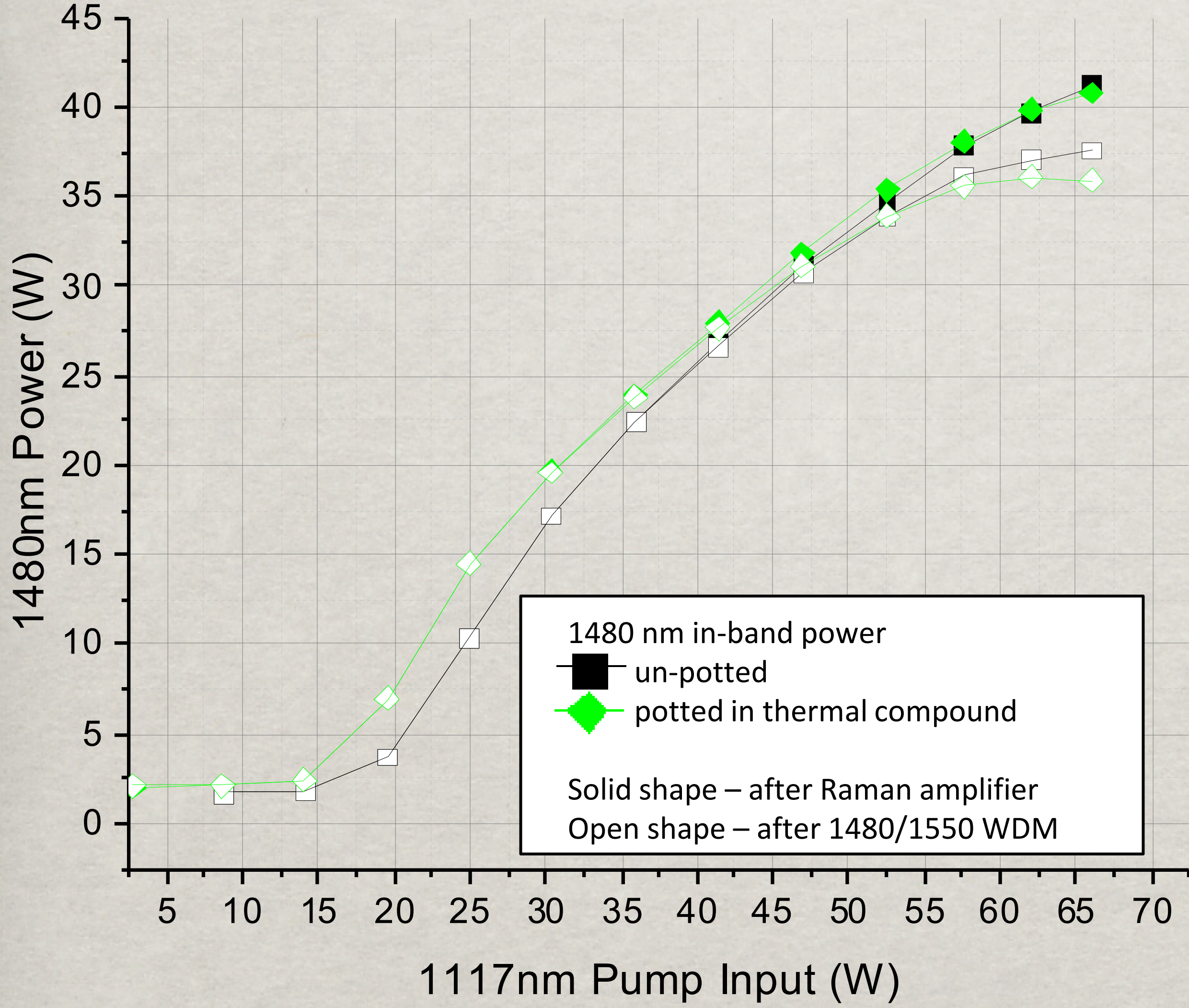
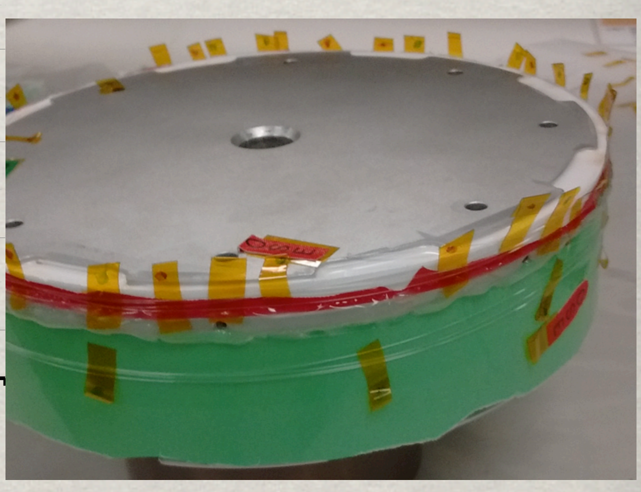
Potting amplifier fiber in thermal compound

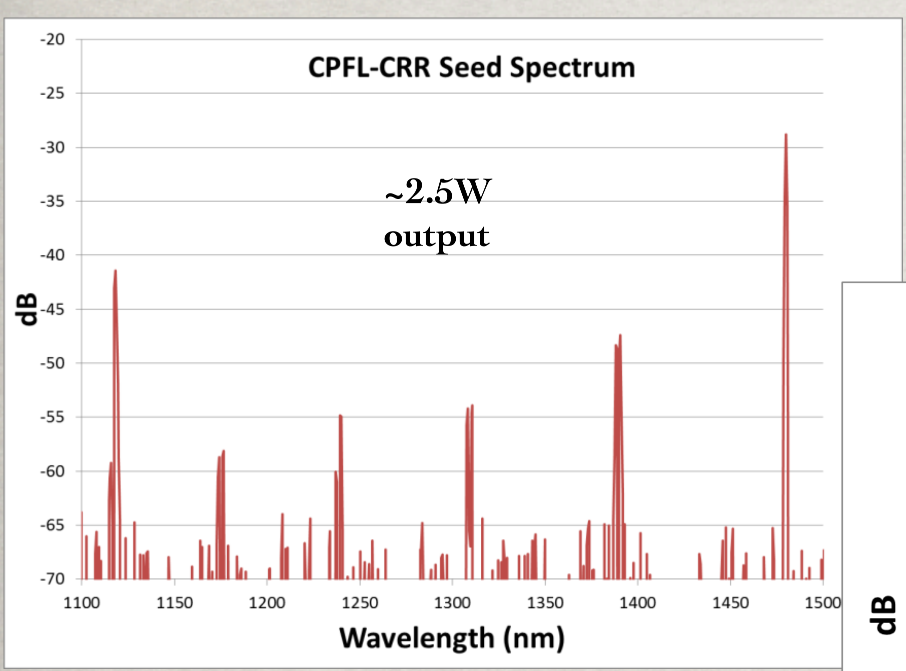


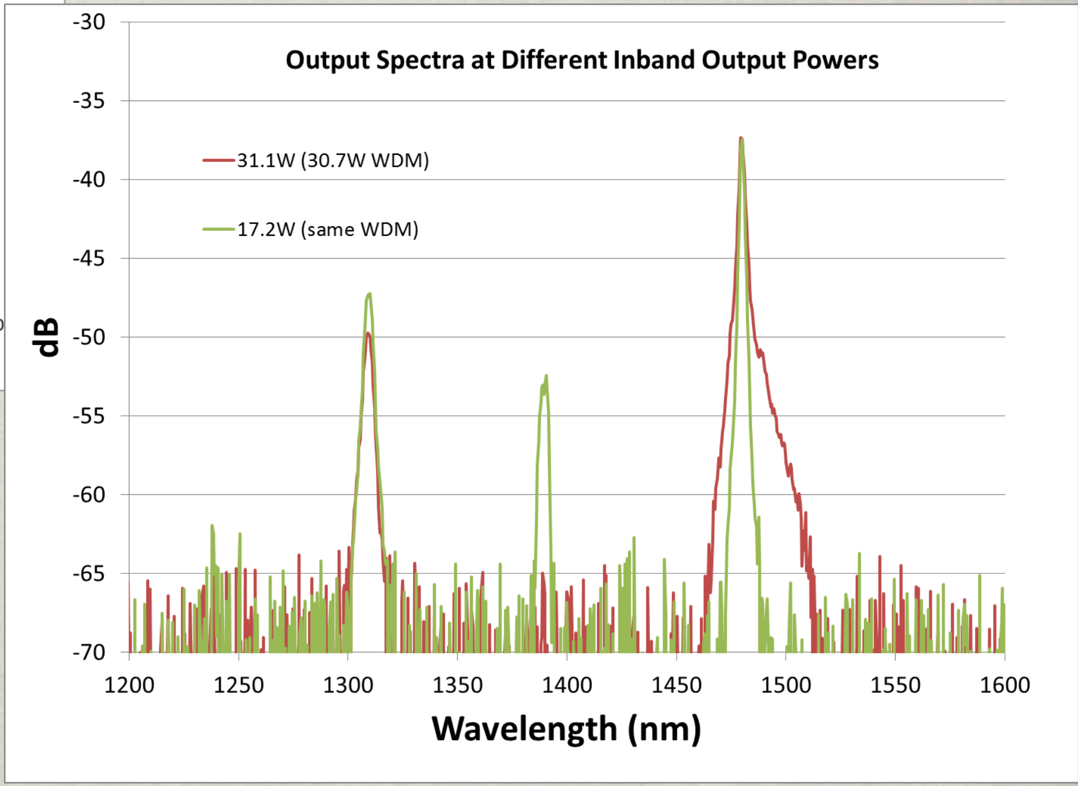
Process of vacuum potting amplifier fibers in thermal compound did not affect Yb or Raman cavity efficiencies. Over-all system efficiency was un-changed after potting process.



Seed and Raman Fiber Laser Output Spectra

GSFC





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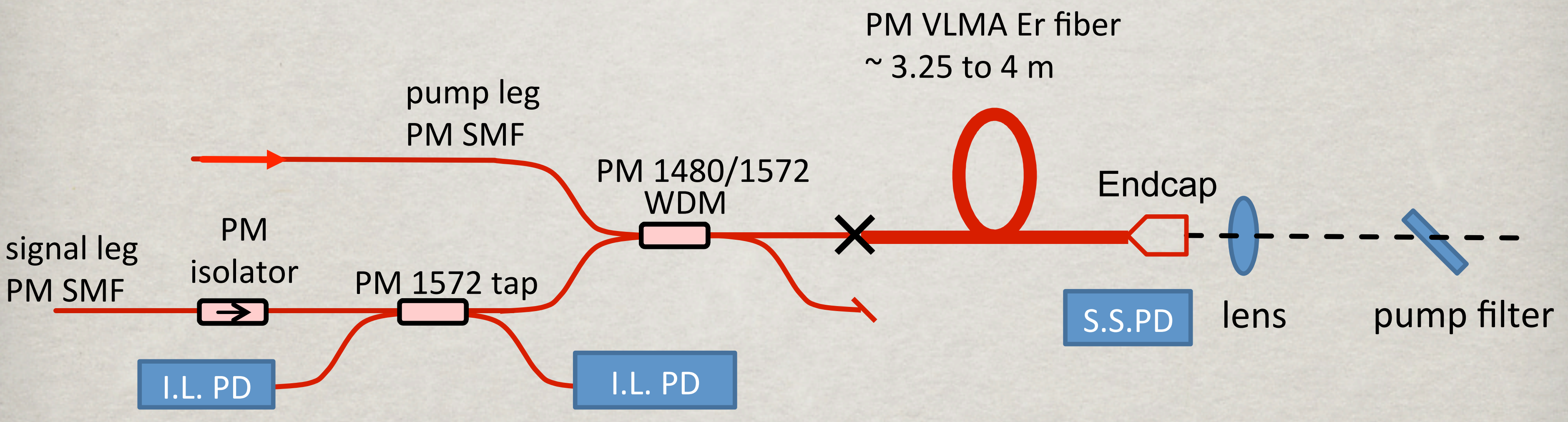
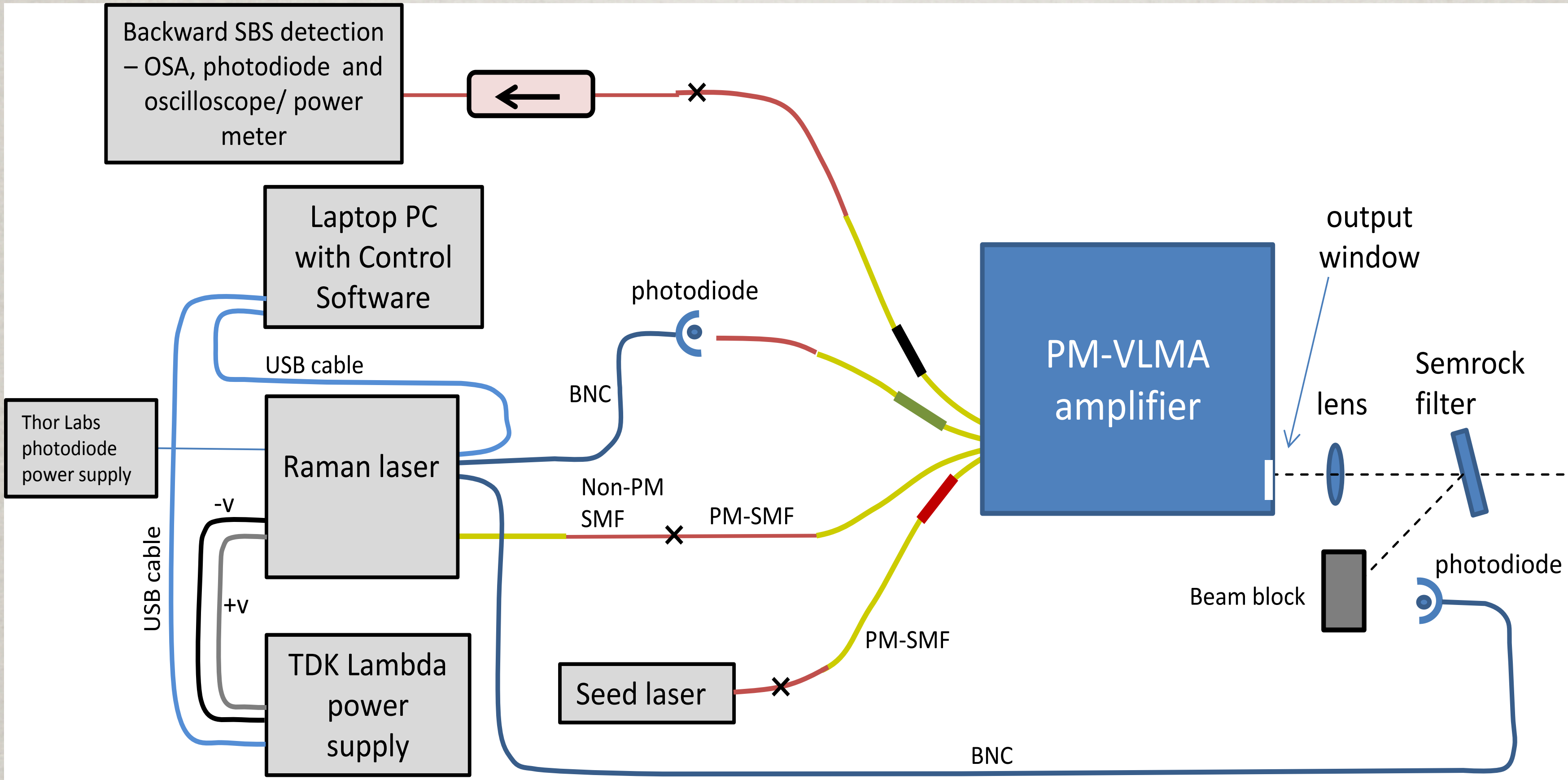
PM-VLMA-Er schematic



VLMA Power Amp Configuration



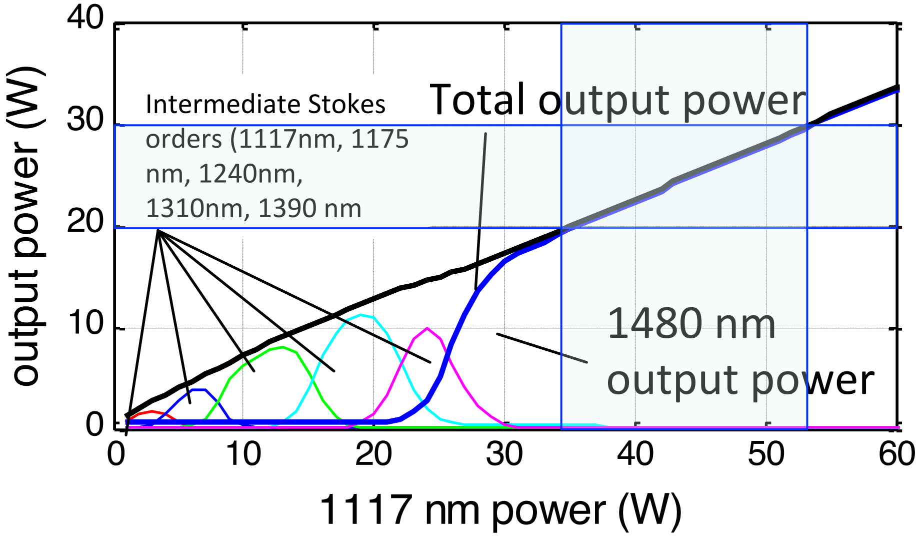
Raman Laser Amplifier Efficiency Summary

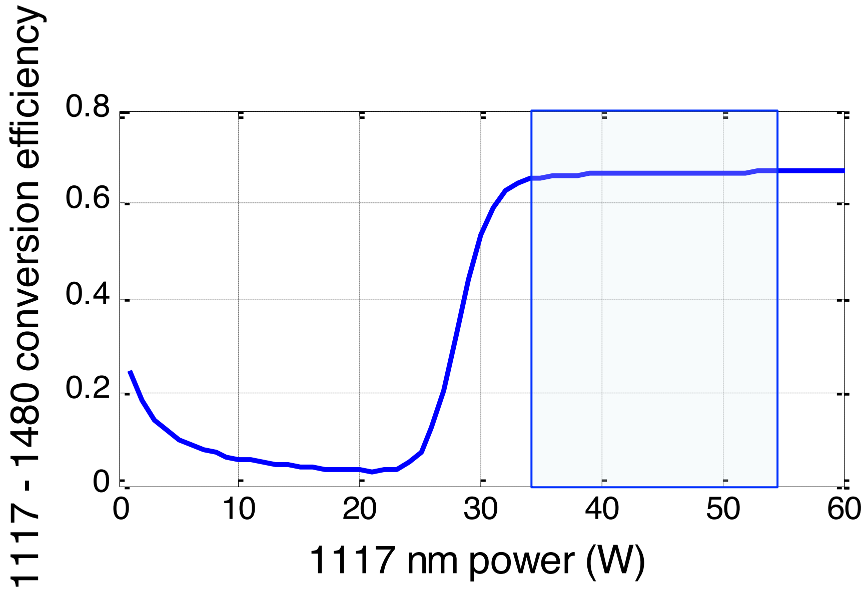
- One single 1480 nm Pump at 30 W for two PM-VLMA Fiber Amplifiers
- Each 30 W Raman laser amplifier at 1480 nm consists of:
  - 1480 nm Raman seed laser at ~1 W
  - 1117 nm Pump source at ~40 W
  - ~500 to 600 m Raman filter fiber
- 975 nm to 1480 nm Overall E-O Efficiency ~50% x 80% x 60%, or ~24%
  - 975 nm Pump Diodes E-O Efficiency ~50%
  - 1117 nm Yb Fiber Laser O-O Efficiency ~80%
  - Raman amplification from 1117 nm to 1480 nm O-O Efficiency ~60%
- Power at 975 nm required to generate 30W at 1480 nm is ~30W/(0.8x0.6), or ~63 W
  - 975 nm laser comes in ~40W module commercially, so three 975 nm lasers operating at 50% derating will meet the requirement.

Simulation of Cascaded Raman Amplifier

ofs
A Furukawa Company

1480 nm Seed power = 1W
Raman fiber length = 550 m





- Simulation of cascaded Raman amplifier – see V.R. Supradeepa et. al. Opt. Lett. 38, 2013
  - Does not include ASE or FWM mixing effects
- Conversion efficiency calculation includes seed power.
- Above approximately 30W of 1117 nm pump power, output is dominated by 1480 nm
- In this simple simulation, pump power and 1480 nm output power can be increased arbitrarily without negative effects.
- Simple simulation predicts high conversion efficiency (>65%) for low power Raman amplifier
  - This isn't true in experiments, as we'll see below.