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

Mark Stephen, Tony Yu, Jeff Chen, Kenji Numata, Stewart Wu, Brayler Gonzales, Lawrence Han, Mike Plants

NASA-GSFC

Mike Rodriguez, Graham Allan, Bill Hasselbrack

Sigma Space Corp.

Jeff Nicholson, Anand Hariharan – OFS, Inc.

Billy Mamakos – Design Interface, Inc.

Outline

- Introduction
- Architecture
  - Seed Module
  - Pre-Amplifier
  - Power Amplifier
- Prototype Package design
- Conclusions

Fiber-laser-Based Technology Development

GSFC

- Fiber lasers have been proposed for several space-based applications
    - Trace-gas spectroscopy, altimetry, laser comm., ranging, robotic vision systems, etc.
- The goal of this program is to demonstrate technology readiness (TRL-6) by building a representative system and completing environmental testing
- Our demonstrator system is a 1.57 µm system for CO_2 spectroscopy

Earth Science Technology Office

Program Objectives

- Demonstrate the key performance requirements for a space-based CO_2 sounder laser transmitter

- Build a prototype and complete environmental testing of the pulsed 1.57μm fiber-based laser transmitter to demonstrate TRL 6

- Remove the last technology hurdle to enable active CO_2 measurements from space using fiber-based laser technology

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)**	**$\leq$ 50 MHz**	**$\leq$ 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 hours 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

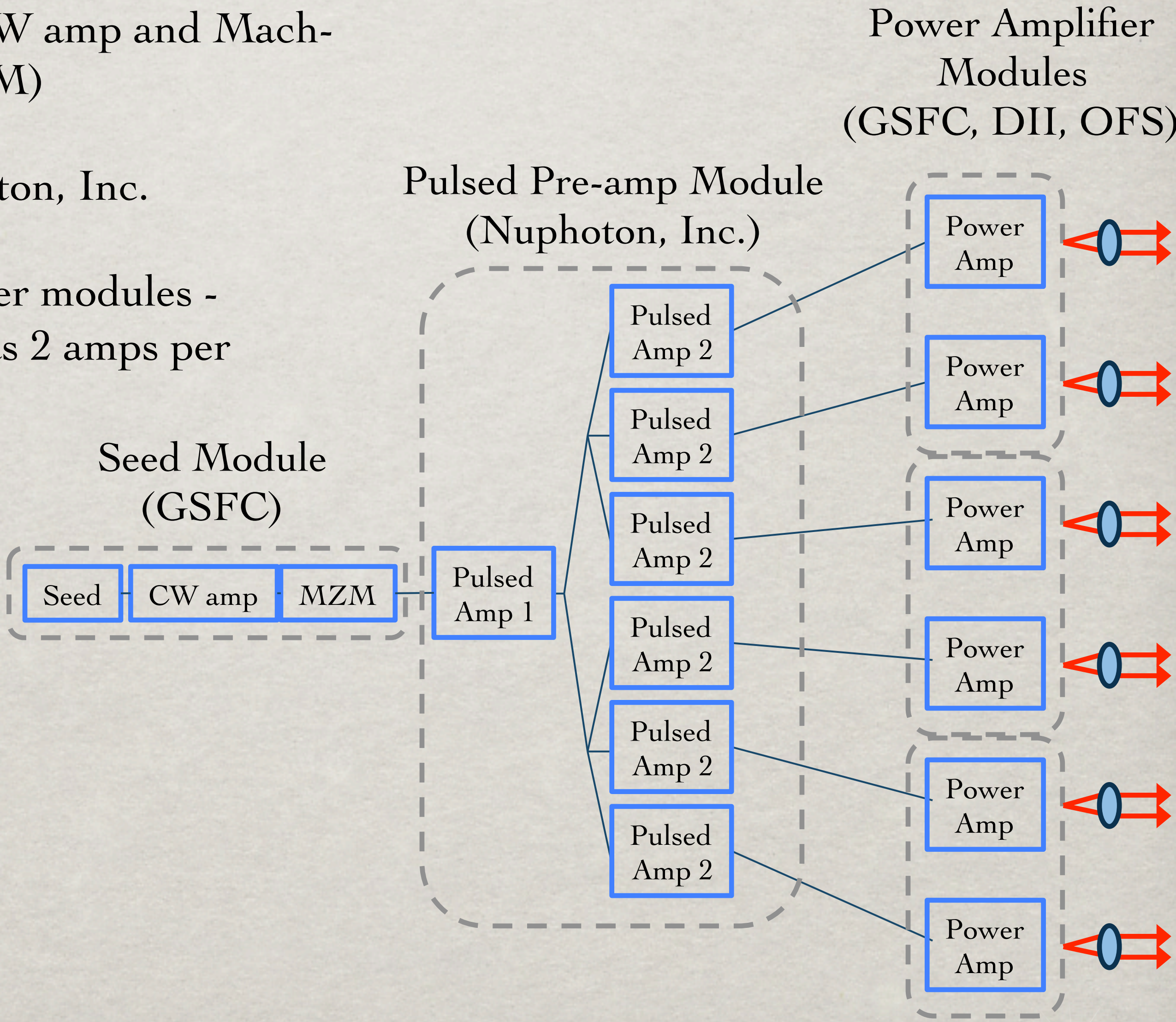
Requirements (2 of 2)

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

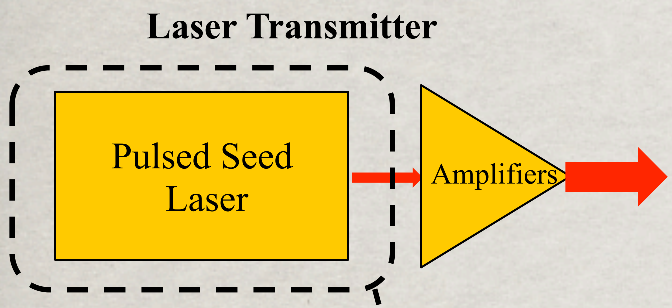
Architecture Overview

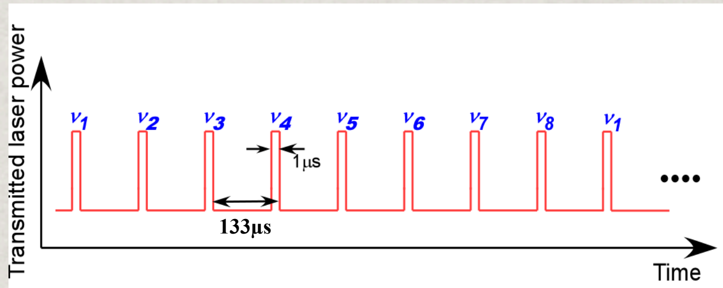
- Seed Module includes CW amp and Mach-Zender Modulator (MZM)
- Pulsed Pre-Amp Module
  - being built by Nuphoton, Inc.
- Power Amplifier
  - Design uses 3 amplifier modules - Packaging concept has 2 amps per module

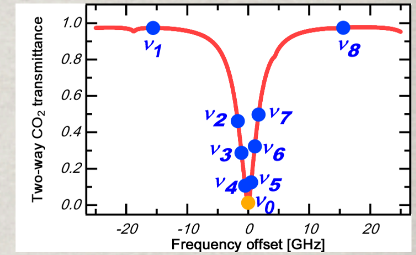


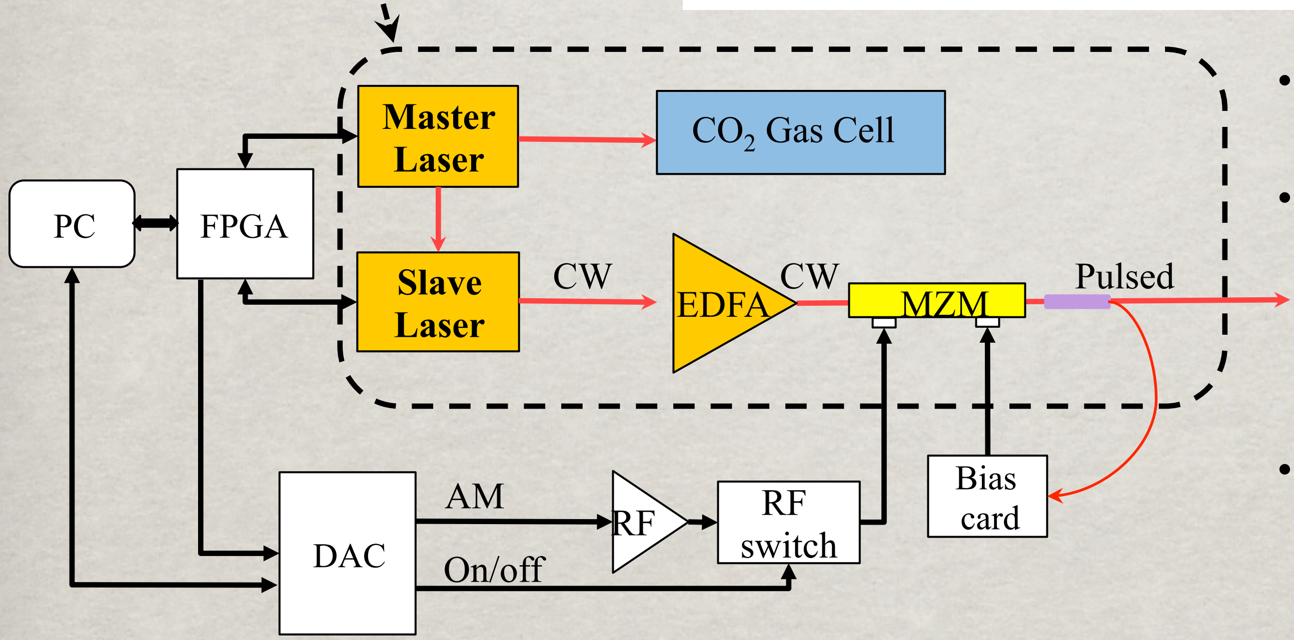
Seed Laser Module

Seed Laser Pulse-Shaping







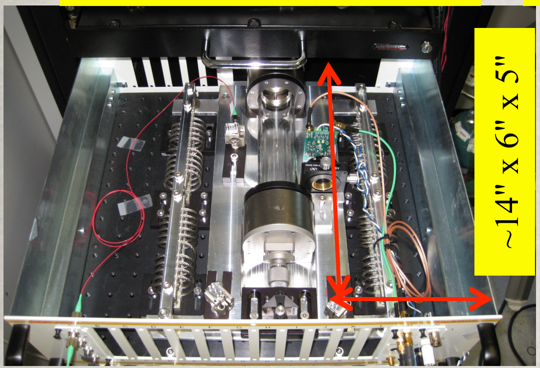


- **The DFB master laser is locked to CO_2 reference cell**
- **A single DS-DBR slave laser is dynamically offset-locked to the master DFB laser using an optical phase-locked loop (OPLL)**
- **The demonstrated laser frequency noise suppression (to < 0.2 MHz), tuning speed (< 40 µs) and tuning range (~32 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

CO_2 Cell Package Options

Existing 17 m CO_2 cell



New 10.1 m CO2 cell

Hockey puck cell (IRsweep)

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

Gas-filled HC-PCF cell

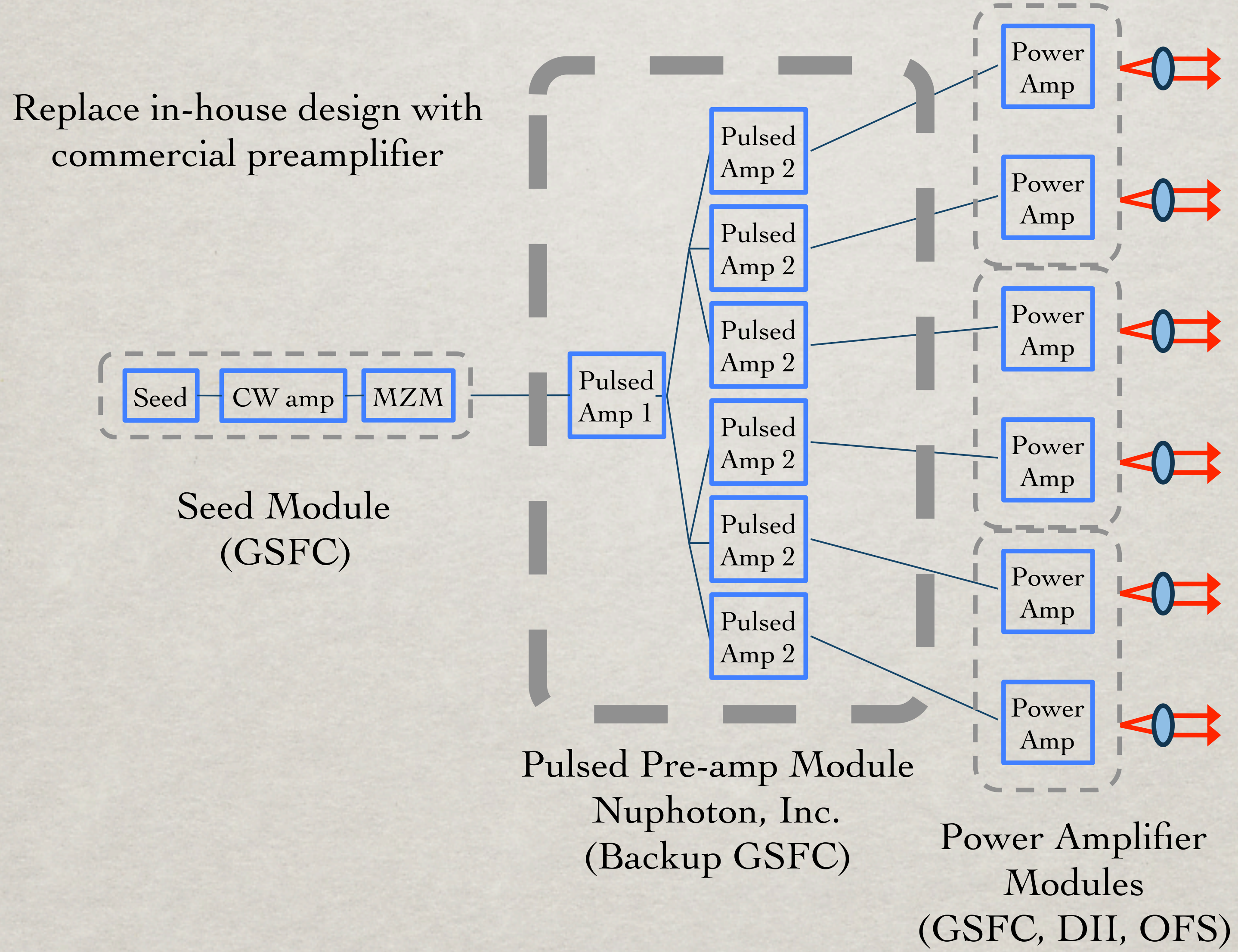
2.5" x 2" x 0.5"

~2" Dia coil

- Our baseline is a 10 meter Herriott cell made by Port City Instruments (received)-**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. Ordered 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.
  - 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

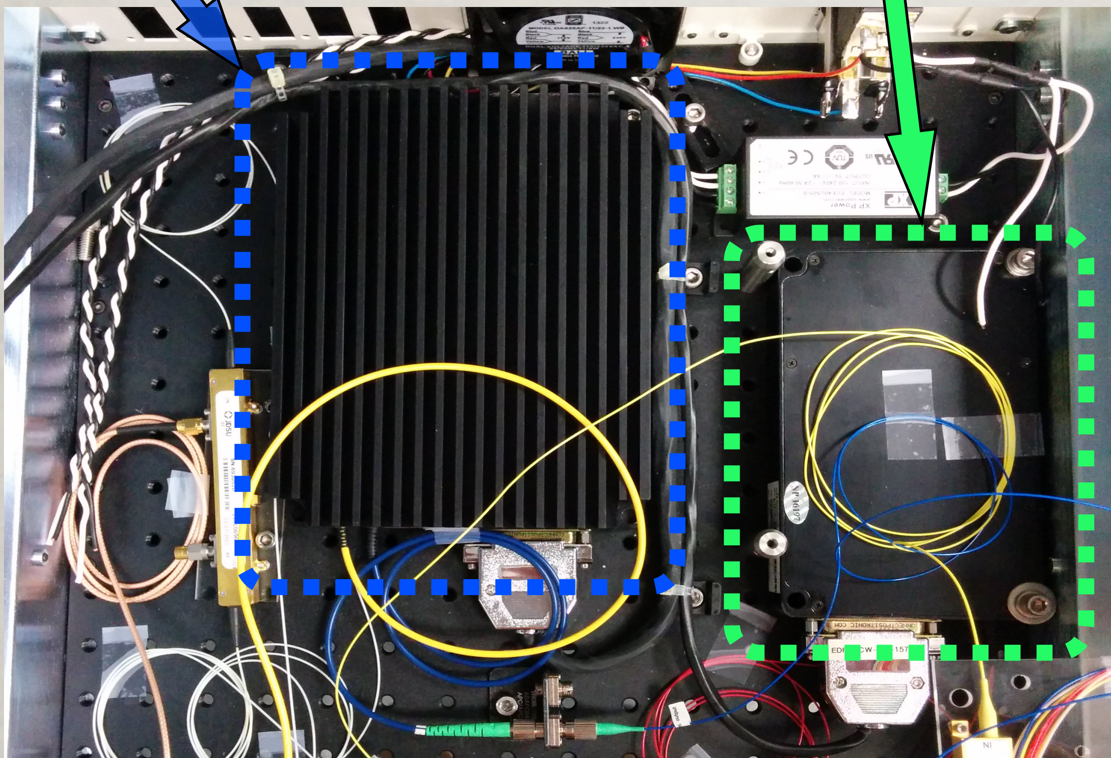


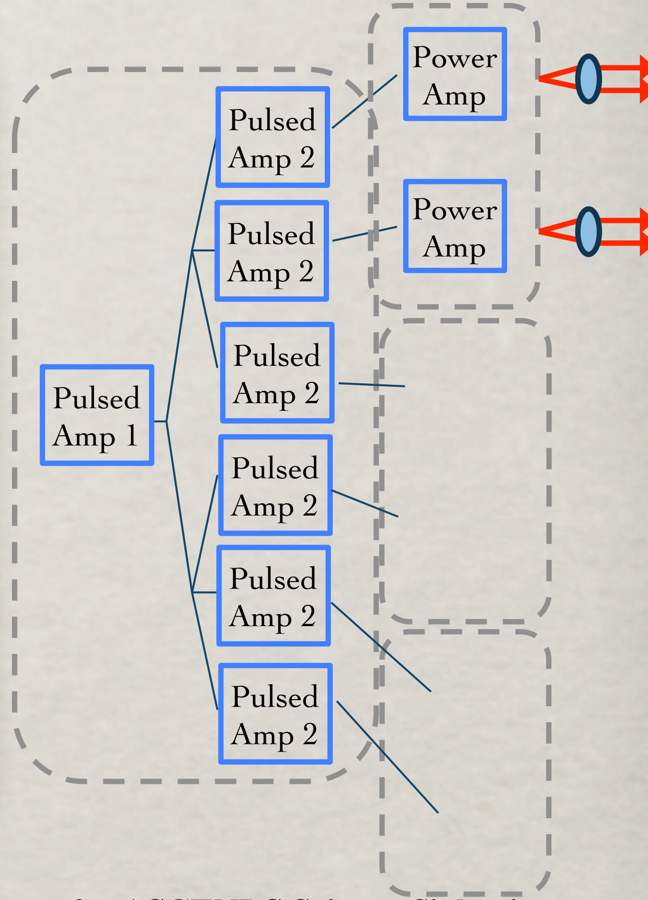
Laser - Preamp - Split 6-ways to seed 6-Power Amps

Commercial EDFA from NUPHOTON

Pulsed Preamp

cw- Preamp



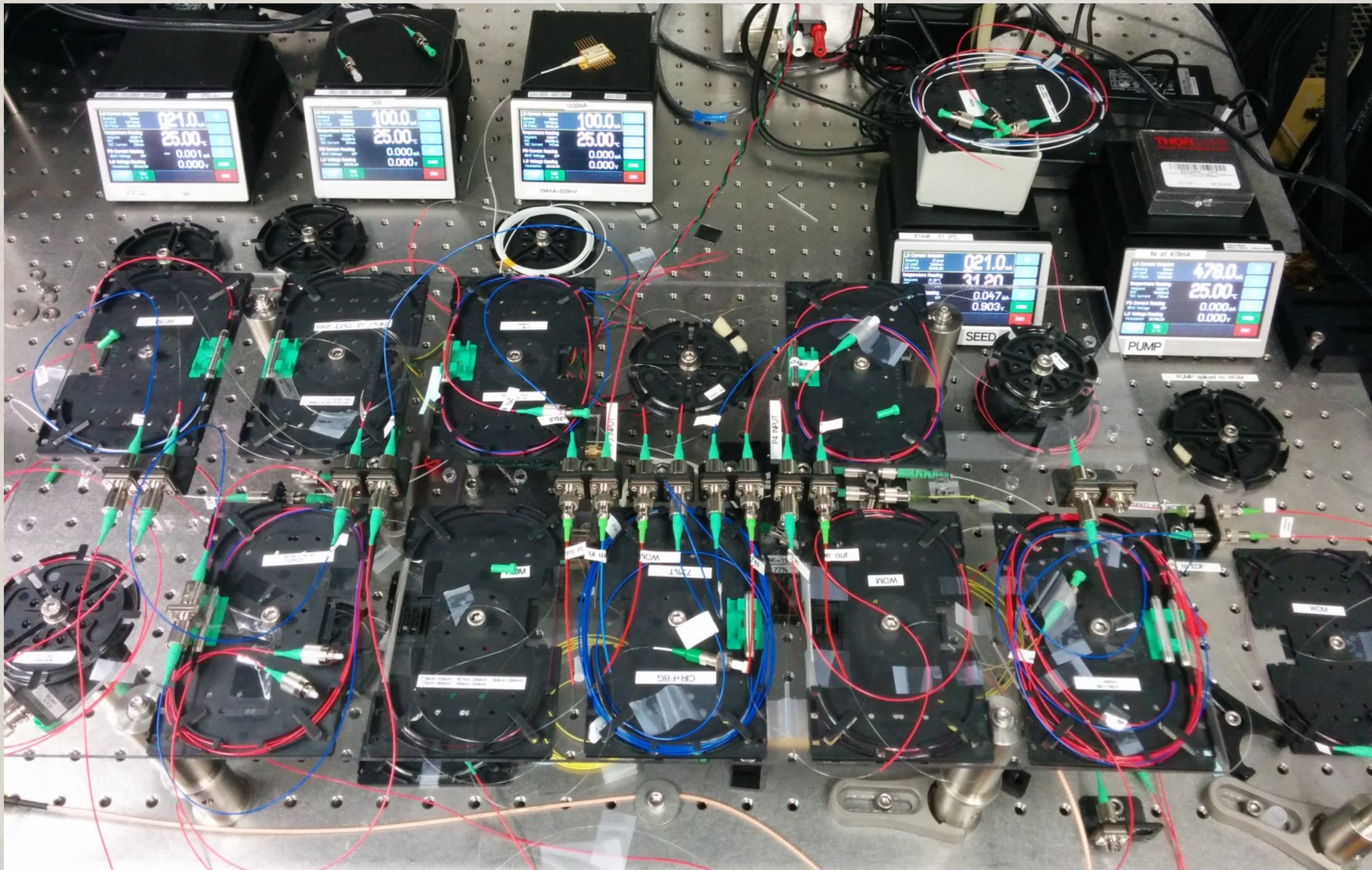


Two similar NuPhoton amplifiers for use in the airborne CO_2 Sounder instrument for ASCENDS Science flights in 2016

NuPhoton flown on ISS in pressurized container

We will use Nuphoton's higher power versions of these amplifiers in the preamp build.

In-house Breadboard Preamp Setup

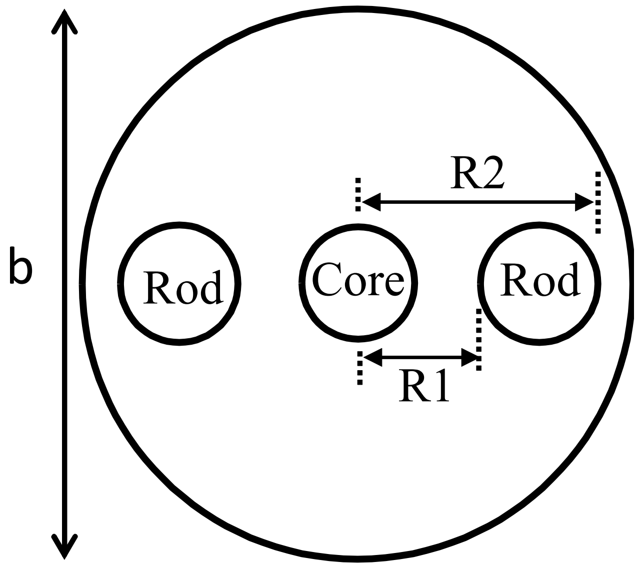


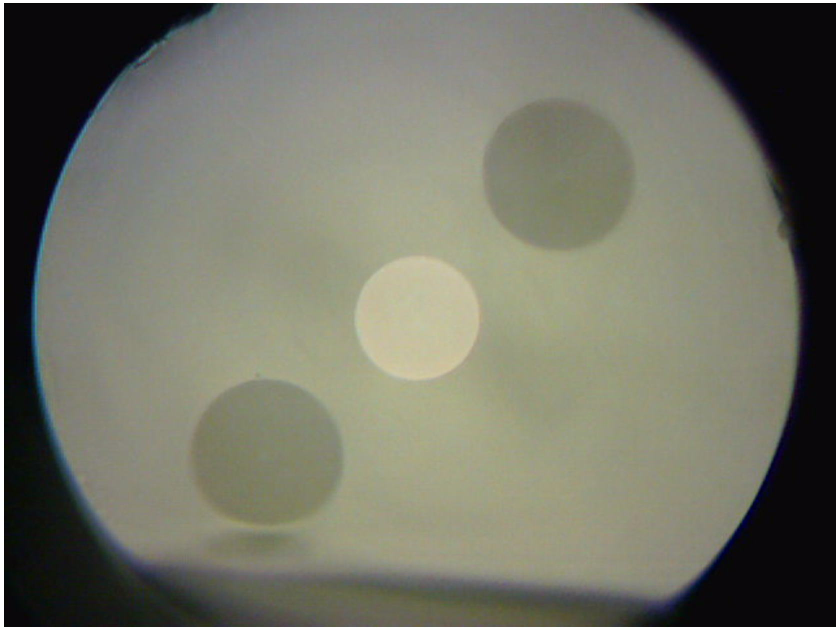
4-Stage preamp: cw-section, modulator and 3 pulsed stages (~30dB gain)
Output pulse energy ~13µJ

Power Amplifier Module

PM VLMA Design

VLMA core radius ~ 25 µm



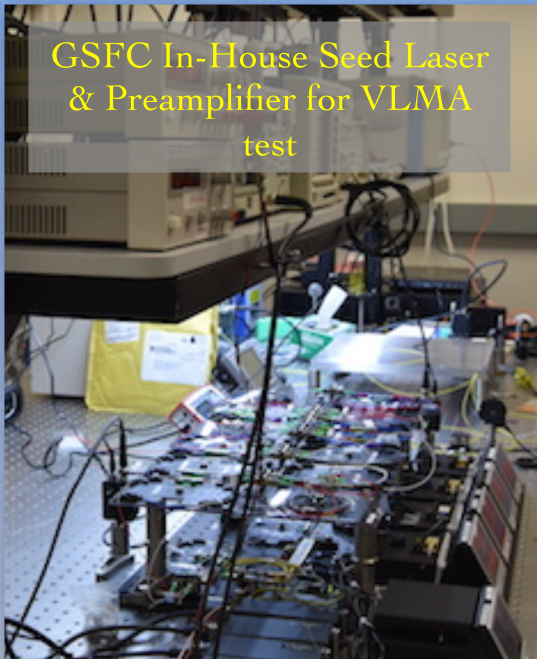


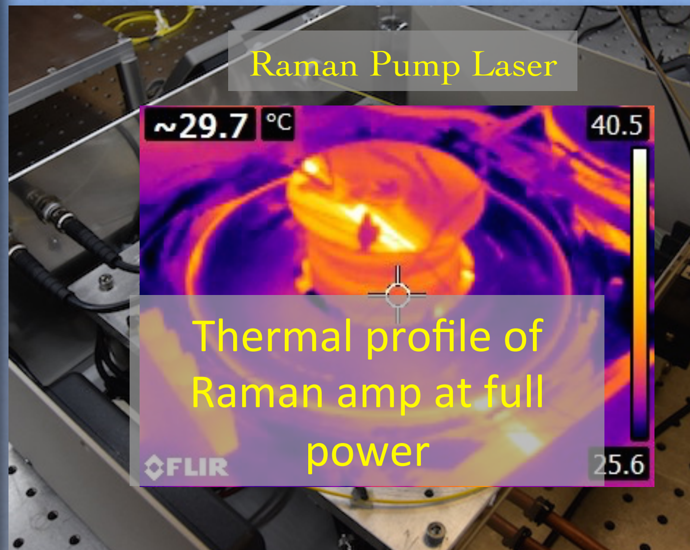
Short birefringence beat length:

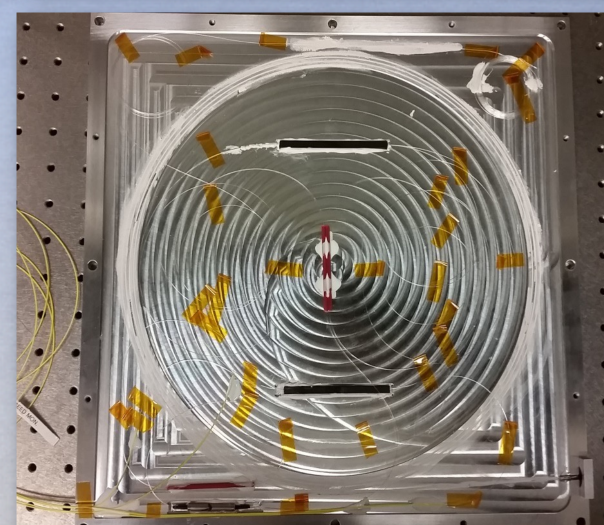
- Important for high PER
- But requires large stress rods very close to core which can cause distortions to the core geometry and make cleaving difficult

Two different PM VLMA fibers were fabricated with different stress rod geometries and beat lengths to test influence of design on amplifier performance

Power Amplifier Breadboard (OFS)

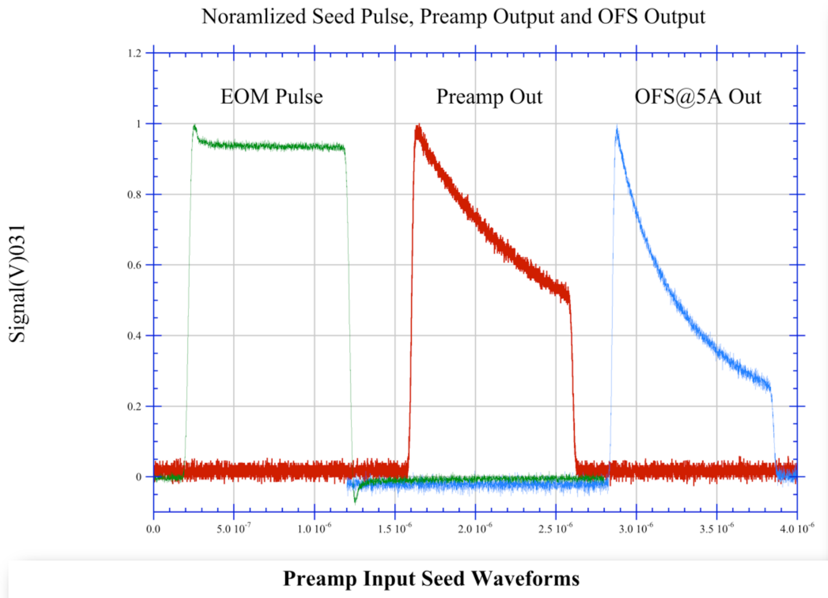


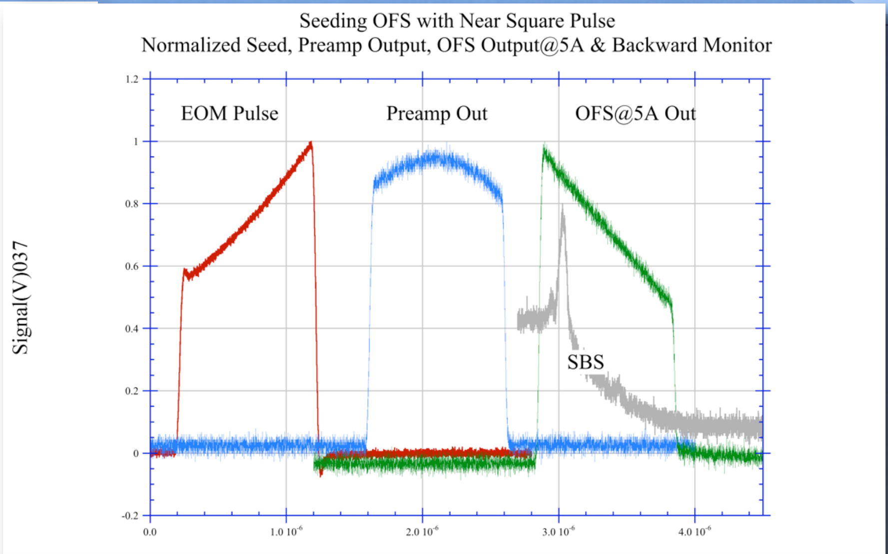


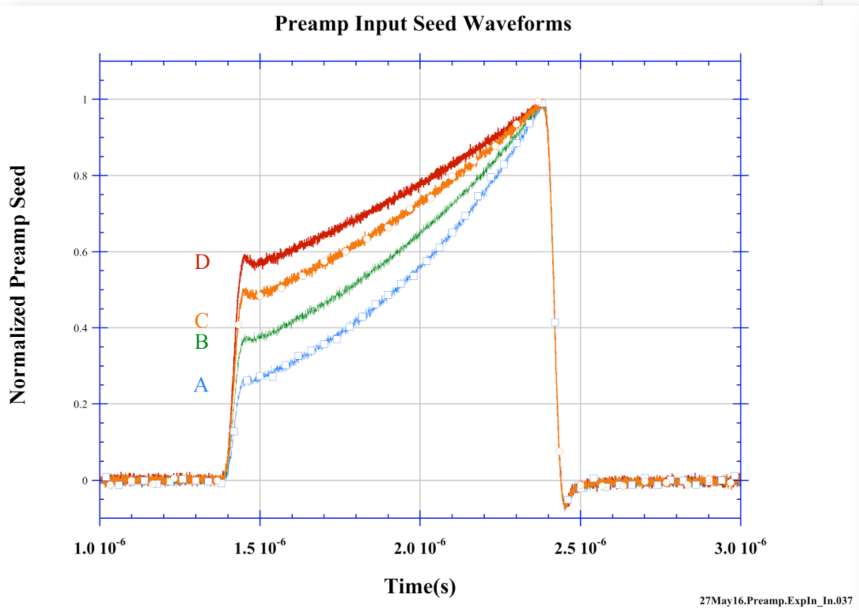


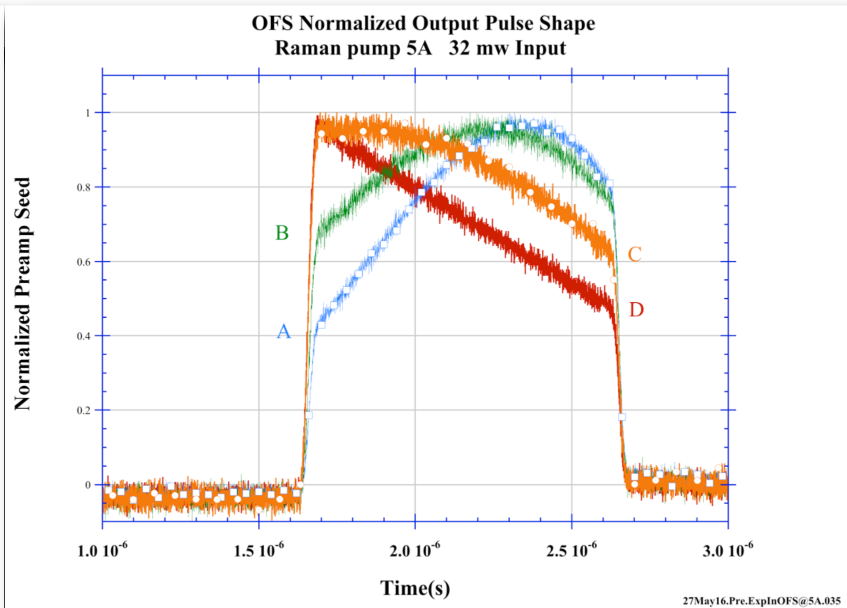
- Maximum Pulse Energy ~560μJ with 4.3μJ in @7.5KHz
  - 6 parallel amps (~20% derated) will emit > 2.7 mJ
- Engineering model of full MOPA now under development
  - Airborne test of single amp early 2017
  - Vibration & vacuum testing September 2017

Shaping Seed Pulse to Optimize Pulse Energy

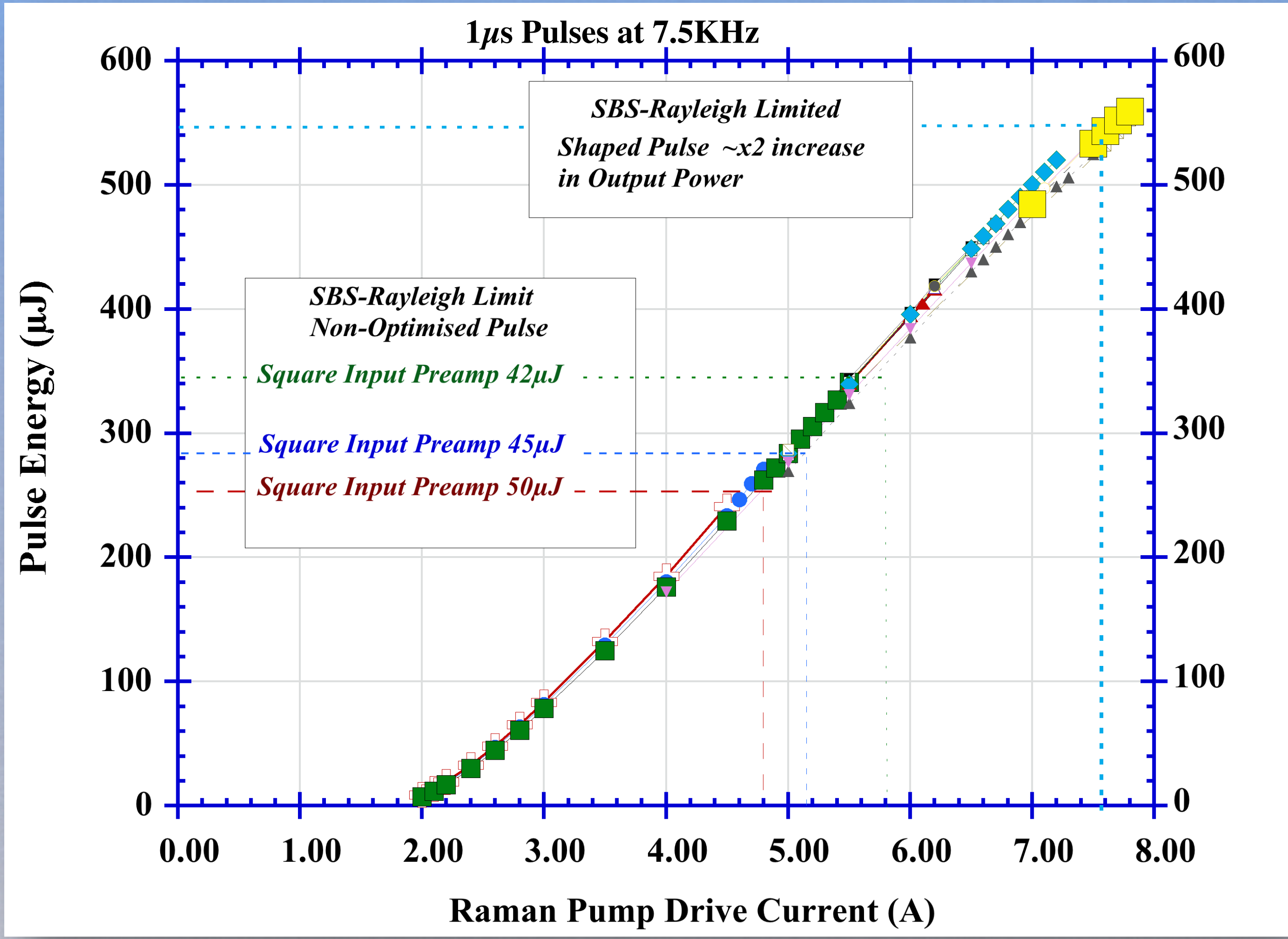






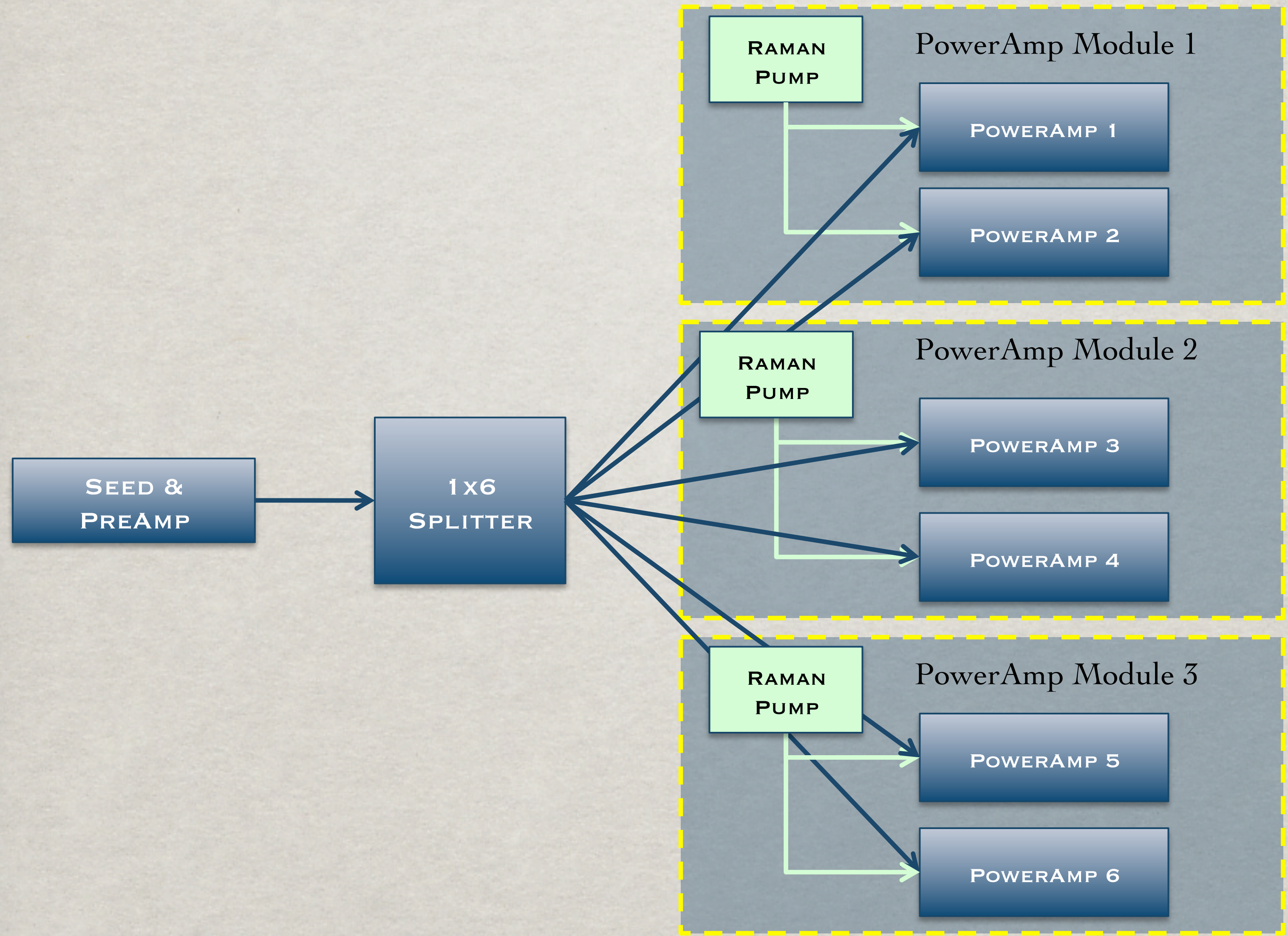


Raman-Pumped VLMA EDFA Output Pulse Energy

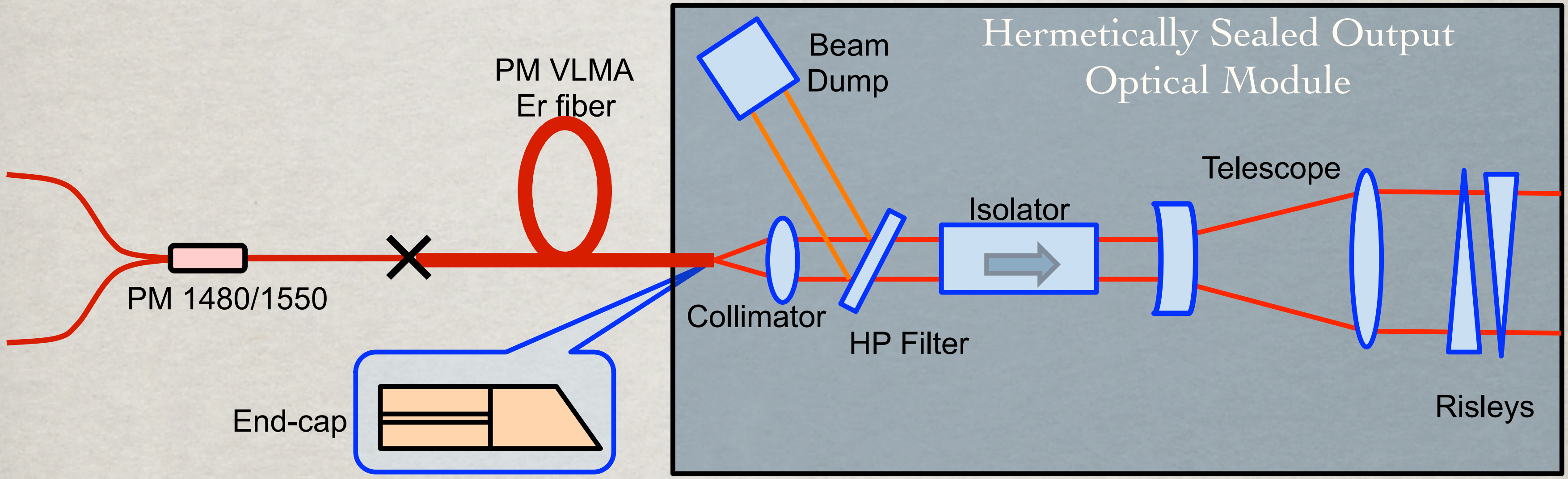


Optimized input pulse shape and energy yields 560 μJ pulse energy from Amplifier

Laser Transmitter Implementation Approach

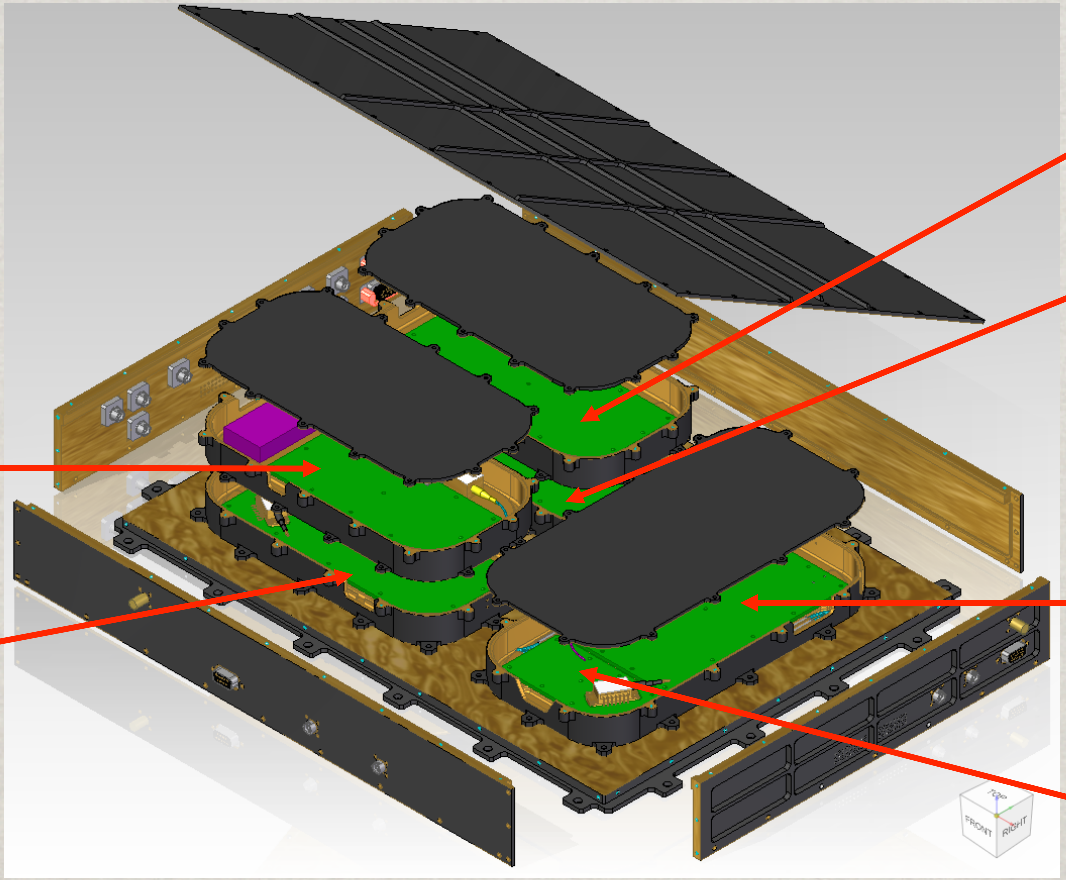


Free-space Optics Module



- PM-VLMA fiber terminated with end-cap which interfaces with the free-space optics module
- One Optics Module per Amplifier
- Hermetically sealed to minimize contamination
- Co-boresighted to allow far field summing of output power

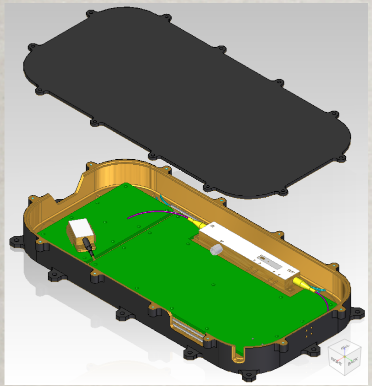
Seed Laser Module Mechanical Design

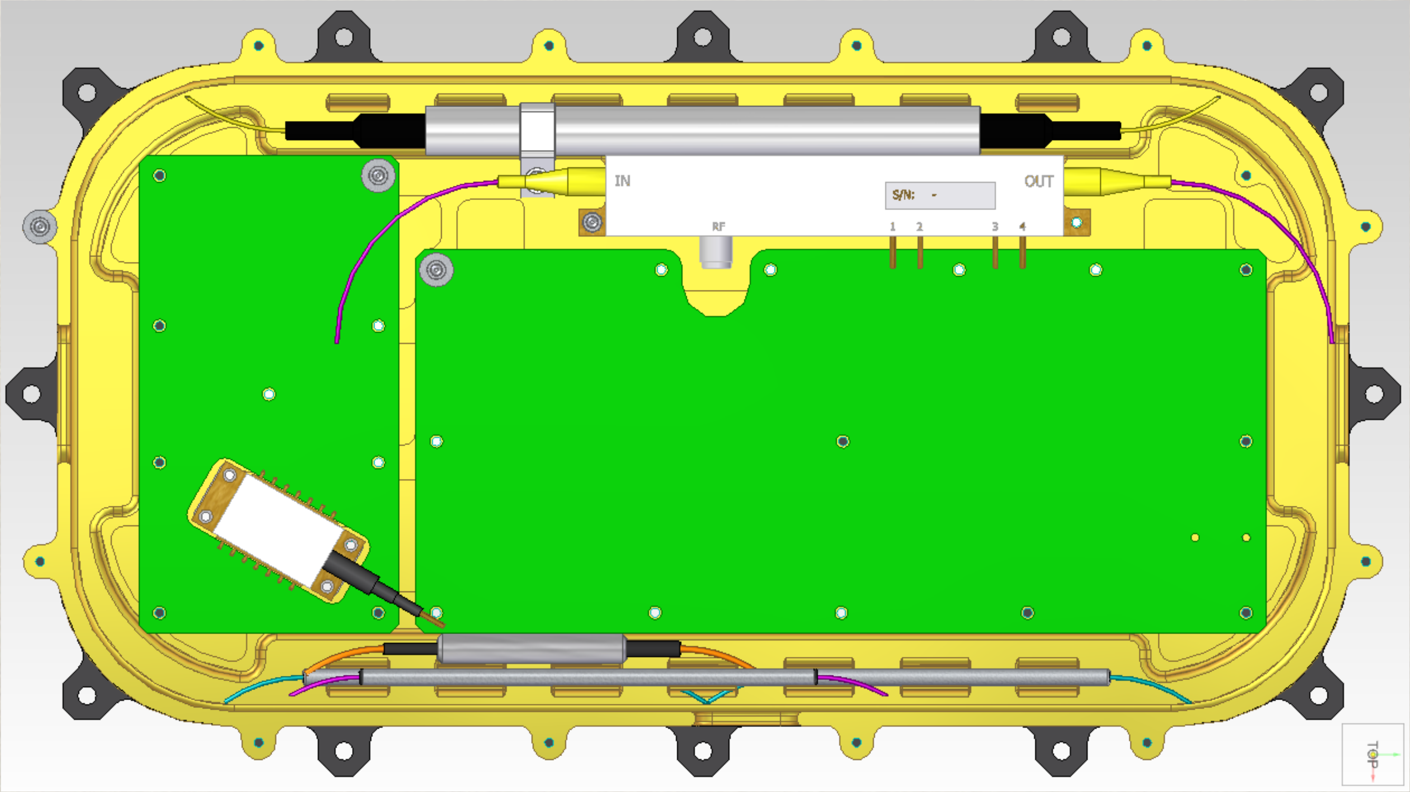


Seed Module
(Exploded Isometric View)

Master and Slave internal modules are made up of multiple slices, this design allows for other supporting electronics to be easily included and integrated (i.e. Driver and Locking Servo Board). The necessary laser components will be taken through environmental testing, leaving other supporting temporarily electronics outside

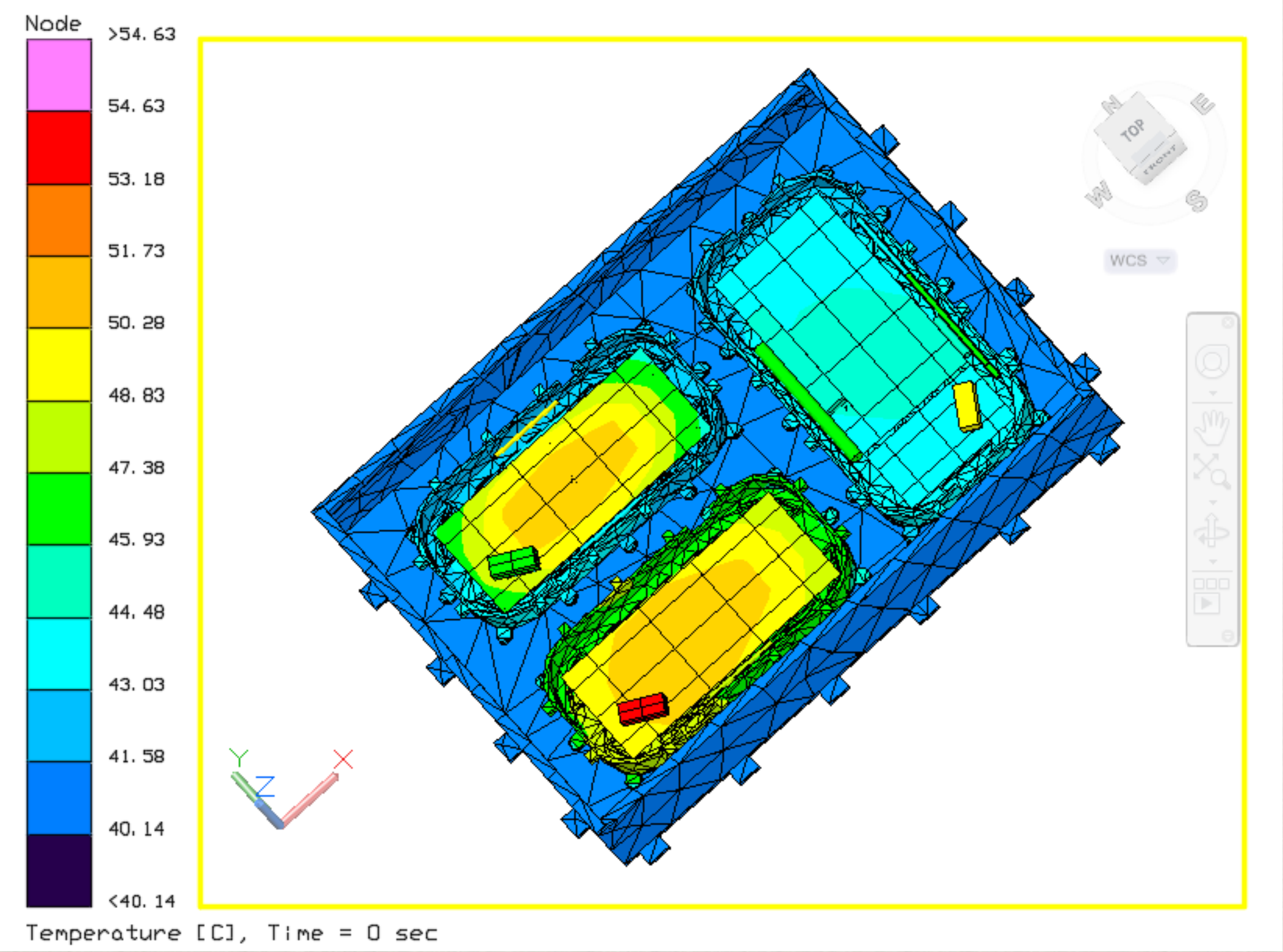
Seed Laser Module: CW Amplifier & Amplitude Modulation Card





Includes: Simplified view of mechanical slice with two boards and a DFB laser with a Amplitude Modulator and various passive laser components.

Temperature Predictions

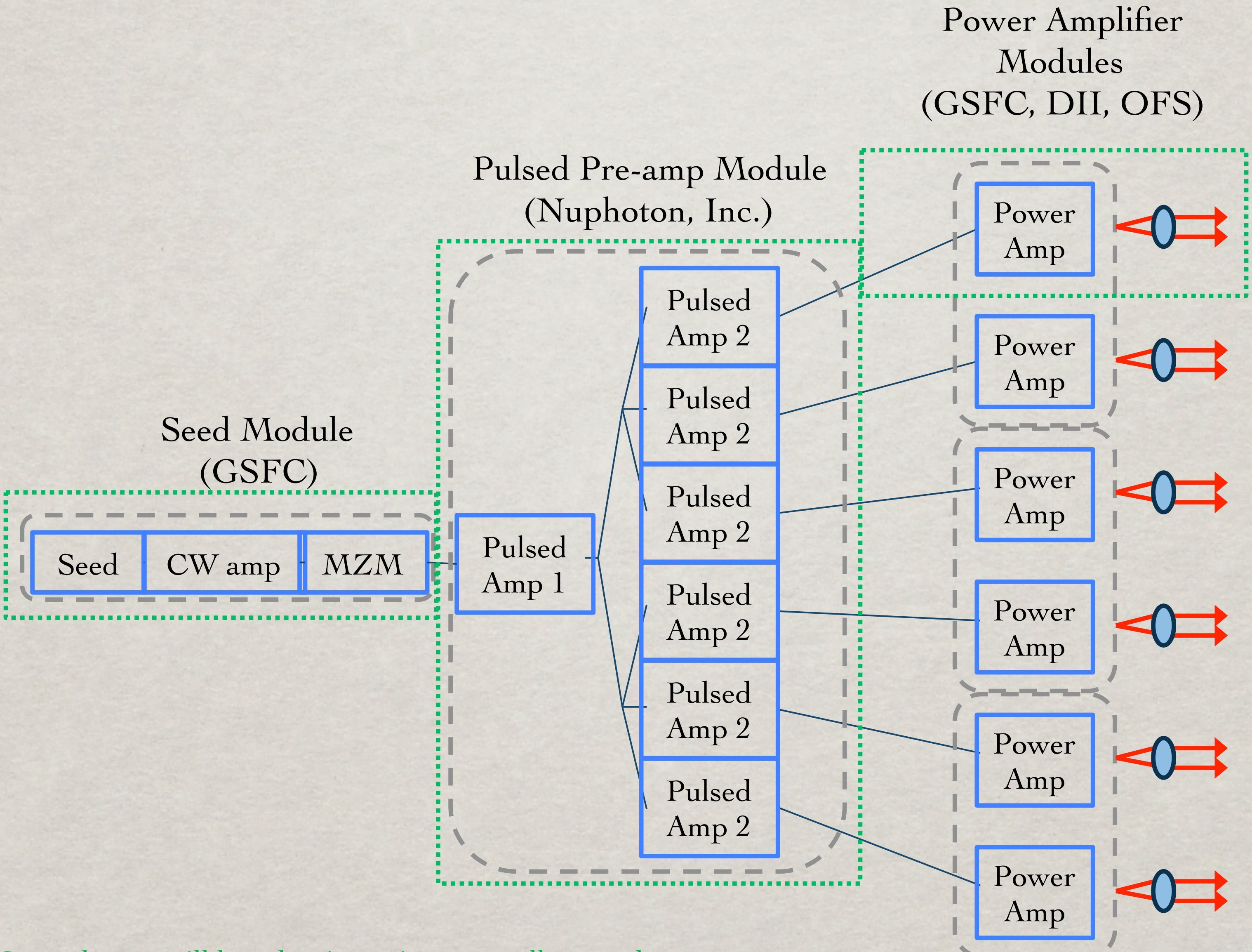


Conclusions

- Demonstrated all optical performance requirements with margin in breadboard
- Mechanical design nearly complete and we have started ‘cutting metal’
- Analysis complete for most of design
- Environmental testing will be conducted in the fall of 2016
- Full power demonstration with 6 amplifier channels scheduled for early 2017

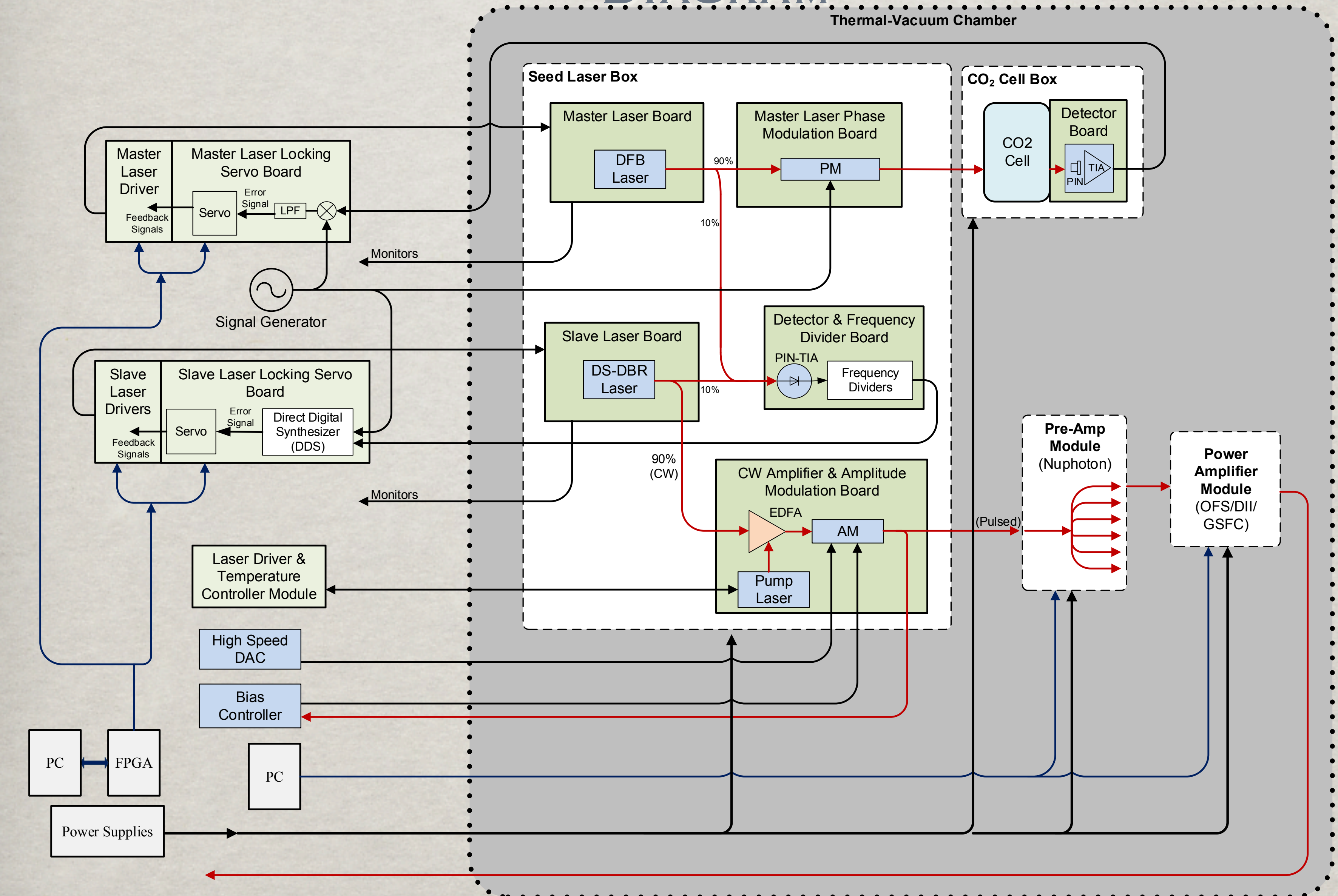
Back-up

TRL 6 Assumptions for proposed plan:



Dotted Green boxes will be what is environmentally tested.

Current Environmental Testing Block Diagram



TRL 6 Environmental Test Plans

GSFC

TRL-6 - Environment

- Vibration – Requirements derived from ISS JEM
- Thermal Vacuum - Requirements derived from ISS JEM
- Radiation – based on calculated total dose ionization for our LEO ISS orbit
- EMI/EMC – TBD depending on electronics included
- Reliability – Performance requirement assessed by analysis with very limited system level life-testing

References

Instrumentation

1. K. Numata, J. R. Chen, S. T. Wu, J. B. Abshire, and M. A. Krainak, “Frequency stabilization of distributed-feedback laser diodes at 1572 nm for lidar measurements of atmospheric carbon dioxide,” Appl. Opt. 50, 1047(2011).
2. K. Numata, J. R. Chen, and S. T. Wu, “Precision and fast wavelength tuning of a dynamically phase-locked widely-tunable laser,” Opt. Express 20, 14234 (2012).
3. P. G. Westergaard, J. W. Thomsen, M. R. Henriksen, M. Michieletto, M. Triches, J. K. Lyngsø, and J. Hald, "Compact, CO2-stabilized tuneable laser at 2.05 microns," Opt. Express 24, 4872 (2016).

Analysis

4. J. R. Chen, K. Numata, and S. T. Wu, “Error reduction methods for integrated-path differential-absorption lidar measurements,” Opt. Express 20, 15589 (2012).
5. J. R. Chen, K. Numata, and S. T. Wu, "Error reduction in retrievals of atmospheric species from symmetrically measured lidar sounding absorption spectra," Opt. Express 22, 26055 (2014).
6. J. R. Chen, K. Numata, and S.T. Wu, "Impact of broadened laser line-shape on retrievals of atmospheric species from lidar sounding absorption spectra," Opt. Express 23, 2660 (2015).

Patents

7. J. R. Chen, K. Numata, S. T. Wu, and G. Yang, “Apparatus and method to enable precision and fast laser frequency tuning," US patent 9,065,242 (2015).
8. (Pending) J. R. Chen, K. Numata, S. T. Wu, “System and method for using hollow core photonic crystal fibers,” US patent application filed by NASA/GSFC (Sept., 2015).