Multi Spectral Lidar (MSL)

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ABSTRACT

We have developed and demonstrated both Ytterbium-doped and Erbium-doped, diode-pumped and seeded, fiber amplifiers at 1064 and 1570 nm, respectively. By pulse pumping a one-stage Erbium amplifier, we have shown greater than 20 W peak output power and high wall-plug efficiency. Our pulse-pumping approach improves energy efficiency up to 80% (at 1 kHz PRF) over the identical CW pumping scheme while suppressing amplified spontaneous emission (ASE). We report on the development of these rare-earth doped fiber amplifiers and the application of multi-stage fiber amplifiers to create a multi-spectral laser transmitter ideally suited for space and planetary lidar investigations.

INTRODUCTION

Laser remote sensing or lidar can make unique and important measurements related to NASA's Vision for Space Exploration. Single wavelength lidar measurements enable three-dimensional maps of planetary surface topography[1], can profile aerosols, plumes, and clouds in planetary atmospheres[2] and can provide altimetry and hazard avoidance information during lander decent and rover operations. In addition, rovers equipped with small imaging lidars can provide high resolution, 3-D images of rocks and interesting geological formations. Adding additional laser wavelength channels to a lidar, creating a multi-spectral lidar, enables active spectroscopy of permanently shaded regions of the moon, i.e. craters near the lunar south pole, trace gas measurement of planetary atmospheres, and spectroscopy of surface composition.

Fiber amplifiers, initially developed for long-haul, fiber optic telecommunications have many potential advantages for use in space due to their compact, rugged and highly efficient nature. Operated at a low duty cycle, short pulse regime, fiber amplifiers at 1064 nm can produce peak powers in excess of 300 kW[3]. Additionally, fiber amplifiers can access a broad wavelength region in the near infrared (1000-1600 nm) that can be extended into the visible region (500-800 nm) using nonlinear, second harmonic generation (i.e. frequency doubling). Research conducted at the Imperial College of London, UK has demonstrated efficient frequency doubling (>40%) of Yb-doped fiber amps to the 3-6 Watt level[4].

Fiber amplifiers alleviate many issues that plague diode pumped solid-state (DPSS) lasers. Laser 2 of ICESAT/GLAS suffered a contamination related failure. Fiber amplifiers eliminate contamination related failures by fusion-splicing all components in a continuous, silica fiber optical path. There is only one glass/air interface, at the final output, that can be protected by fusing a large diameter (~1 mm) glass rod onto it, reducing the fluence. Conducting materials analysis to assure the long-term reliability of laser diodes can mitigate packaging related-failures in pump laser diodes. One important distinction for fiber amplifiers is the use of single element pump laser diodes over traditional diode bars. Currently, a photonics group at NASA Goddard is analyzing laser modules for their ability to withstand long term usage in harsh environments through materials analysis that includes a Destructive Physical Analysis (DPA). DPA was used to identify the packaging related failure modes in the GLAS laser diode arrays. DPA is currently being coordinated with a current internal research and development program to raise the technology readiness level (TRL) of diode laser pump technology.

Rare-Earth (RE) doped gain fiber is being characterized for space flight radiation environments at NASA Goddard. The radiation study will not only raise the TRL of the proposed system by eliminating unanswered questions about radiation induced darkening but the study will include methods of adding pumps lasers for mitigating radiation induced effects using photo-bleaching. NASA Goddard is also providing expertise and knowledge of the physics of failure for mitigating the risk at the component level prior to actual space flight prototype development. Understanding the component level failure modes is necessary to avoid the possibility of these failures occurring during a flight mission. NASA Goddard is involved with fiber laser component level investigations for projects including the Laser

Interferometer Space Antenna (LISA), the Mars Laser Communications Demonstration (MLCD), the Instrument Incubator Program (IIP), and the Air Force Research Labs (AFRL).

Our goal is to demonstrate pulsed laser transmitters capable of 100 uJ pulses, 10 nS wide (peak power of 10 kW) and a PRF of 150-1000 Hz at both 1064 nm (Ytterbium) and 1570 nm (Erbium).

APPROACH

Our approach to developing a multi-wavelength laser transmitter for space and planetary lidar applications involves developing single and double stage amplifiers employing both Erbium and Ytterbium doped fiber operating at 1.5 µm and 1.06 µm respectively. The amplifiers are seeded and pumped with single mode laser diodes that are frequency stabilized with fiber Bragg gratings (FBG). Single mode gain fiber is used with co-propagating single-mode pump laser diodes coupled with WDM combiners for the first stage and large mode area (LMA) fibers pumped with single mode 980 pump diodes for the second stage. In order to maximize wall plug efficiency, we hypothesized that pulse pumping each stage of the amplifier would increase the overall efficiency by suppressing the amplified spontaneous emission (ASE). Frequency doubling the output of these seeded amplifiers with periodically-poled materials such a lithium-niobate or KTP will access the visible to near infrared portion of the spectrum (520 - 785 nm). Core pumping with single mode, 980 nm laser diodes was chosen over clad pumping due to the availability of high-power, single mode, fiber coupled pump lasers.

1. Erbium Fiber Amp Development

A one stage, diode seeded, bi-directionally pumped (i.e. co-propagated pumps) fiber amp using Erbium doped fiber was assembled and tested. A block diagram depicting the one-stage amp is shown in Figure 1. A Wavelength Division Multiplexing (WDM) combiner was used to combine the 980 nm pump with the 1550 nm seed and an identical combiner was used to reverse-propagate a second 980 nm pump laser while singling out the amplified 1550 nm signal.

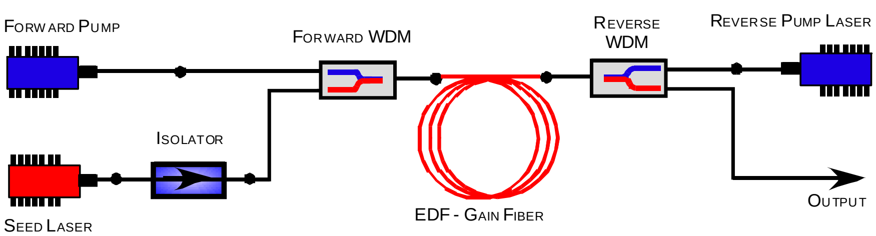


Figure 1. Block diagram of single stage Erbium fiber amplifier.

Modeling results using a vendor-supplied application designer were deemed too ambiguous to be useful so our approach was to experimentally establish the performance and behavior of the amplifier using decreasing lengths of gain fiber. Two meters of high concentration, Erbium-doped single mode gain fiber (Liekki Er110 4/125) were spliced into the amplifier. Data was acquired while varying the seed current effectively controlling the optical seed power coupled into the fiber amplifier while the output power was recorded. Figure 2 shows the CW output power as a function of seed laser current with no pumping, forward pumping only, reverse pumping only and with both pumps operating. Small signal gains in excess of 30 dB are evident when the seed source is coupling approximately –30dBm or 1 µW into the amplifier. With increasing seed power, the gain saturates and no additional output power is realized. Interestingly, reverse pumping alone improves performance over forward pumping alone by almost a factor of two (3 dB) while both forward and reverse pumping together increase performance

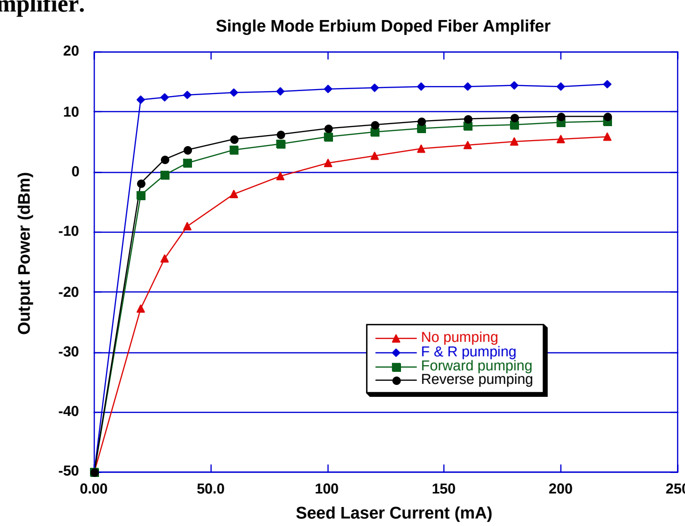


Figure 2. Ouput power (CW) as a function of seed current and pumping conditions for a single stage Erbium fiber amplifier.

over reverse pumping by almost an order of magnitude (10 dB) indicating that the threshold for fiber transparency had be achieved after which output power should scale linearly with pump power. For each gain fiber length, data was acquired using 100, 200, 300 nS seed pulses and varying the pump pulse length. Figure 3 shows peak output power as a function of pump pulse length and gain fiber length. The seed laser was pulsed at 150 Hz pulse repetition frequency (PRF) with a 100 nS pulse width.

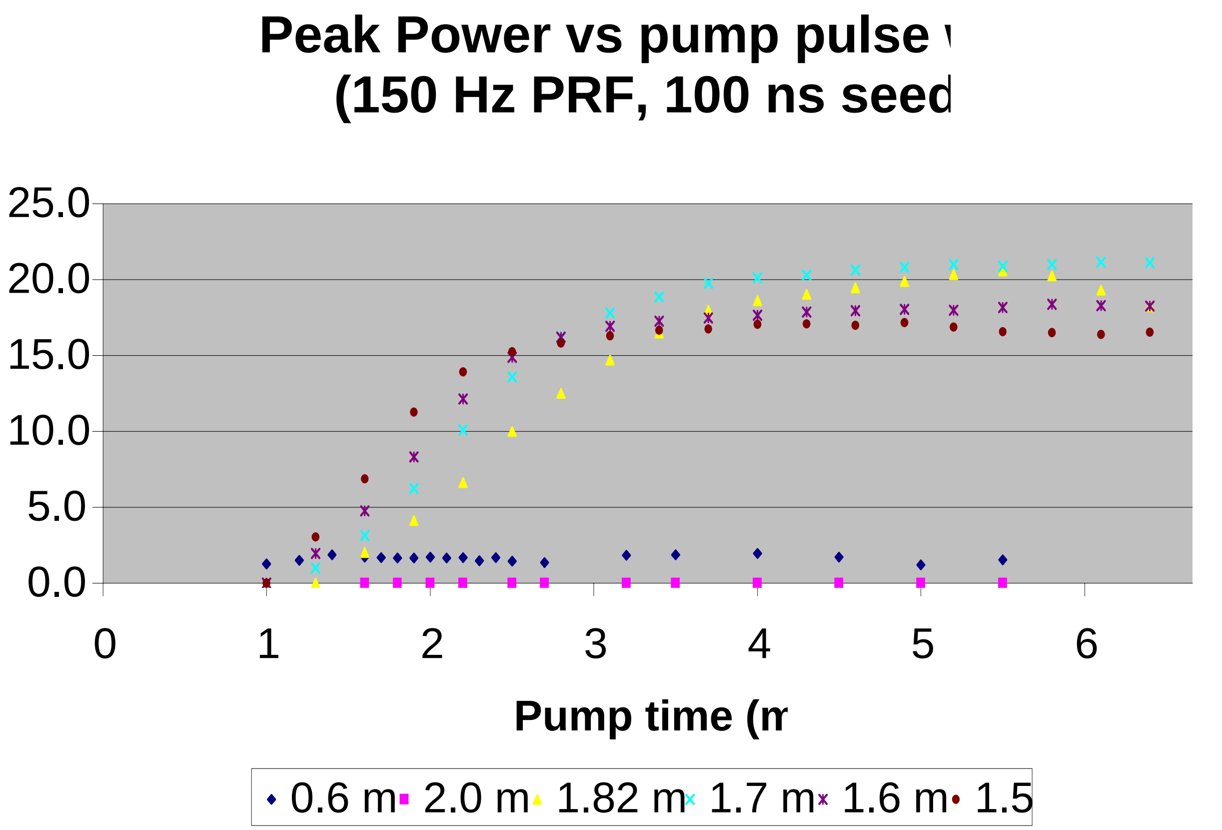


Figure 3. Peak output power for first stage Er^{+3} doped fiber amp as a function of pump pulse length and gain fiber length.

From the graph it is clear that there is a range of gain fiber lengths that results in positive, efficient gain. Further, that increased gain fiber length takes a longer time to energize which can be seen as a change in slope, i.c. steeper, of the curves as the gain fiber is shortened. Ideal gain fiber length in this case is approximately 1.7 meters. Figure 4 shows a picture of the actual two-stage Erbium amplifier set up in the laboratory depicting fiber optical components mounted to an aluminum breadboard, pump lasers and seed laser mounted to standard 14 pin butterfly mounts, temperature controllers and driver electronics. The first stage amplifier was carefully wrapped around pie-shaped segements along the length of the breadboard. Pump and WDM fiber pigtails were wrapped around stacks of similar aluminum segements within the gain fiber. Some interference between the first stage pumps was noticed but mitigated by rewrapping the pump fiber pigtails around smaller diameter spools creating losses within the fiber. Figure 5 shows the block diagram of the two-stage Erbium amplifier set up in Figure 4. In addition to the optical isolator separating the two gain stages a narrow band pass filter is being procured to limit ASE from leaking into the second stage from the first and getting amplified. However, it is possible that with careful tailoring of the timing of the seed pulse, first stage pump pulse and second stage pump pulse that the ASE can be sufficiently suppressed. This will be investigated.

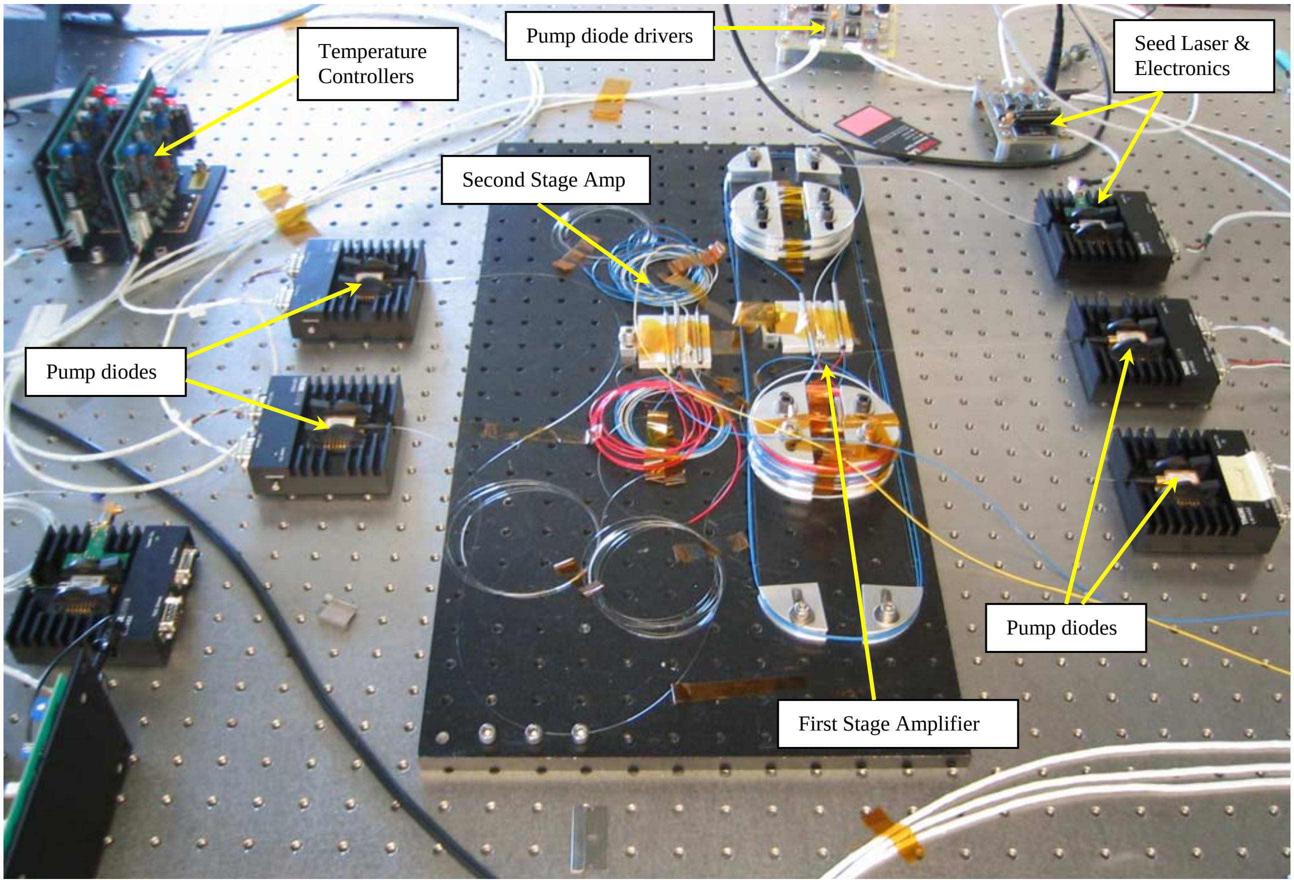


Figure 4. Picture depicting two-stage Erbium-doped fiber amplifier set up. All pump and seed lasers mounted in identical mounts with identical temperature controllers.

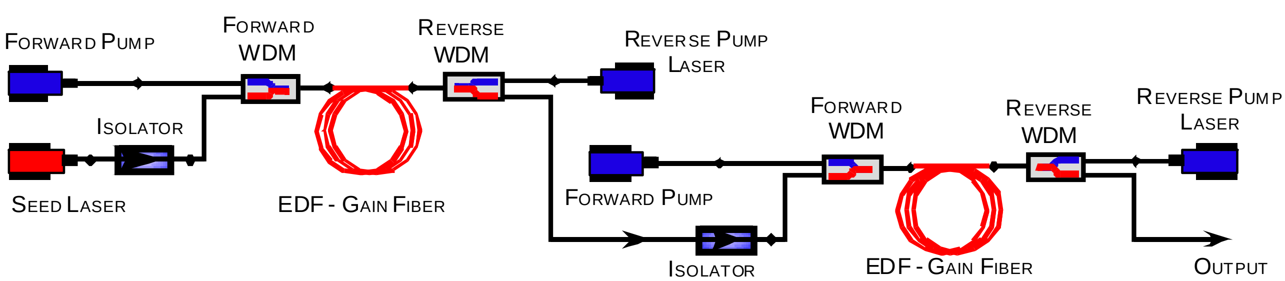


Figure 5. Block diagram of a two stage Er+3 doped fiber amplifier. Note isolator between stages. Narrow bandpass filter centered on seed laser wavelength will be added to prevent ASE from first stage from leaking into second stage and getting amplified.

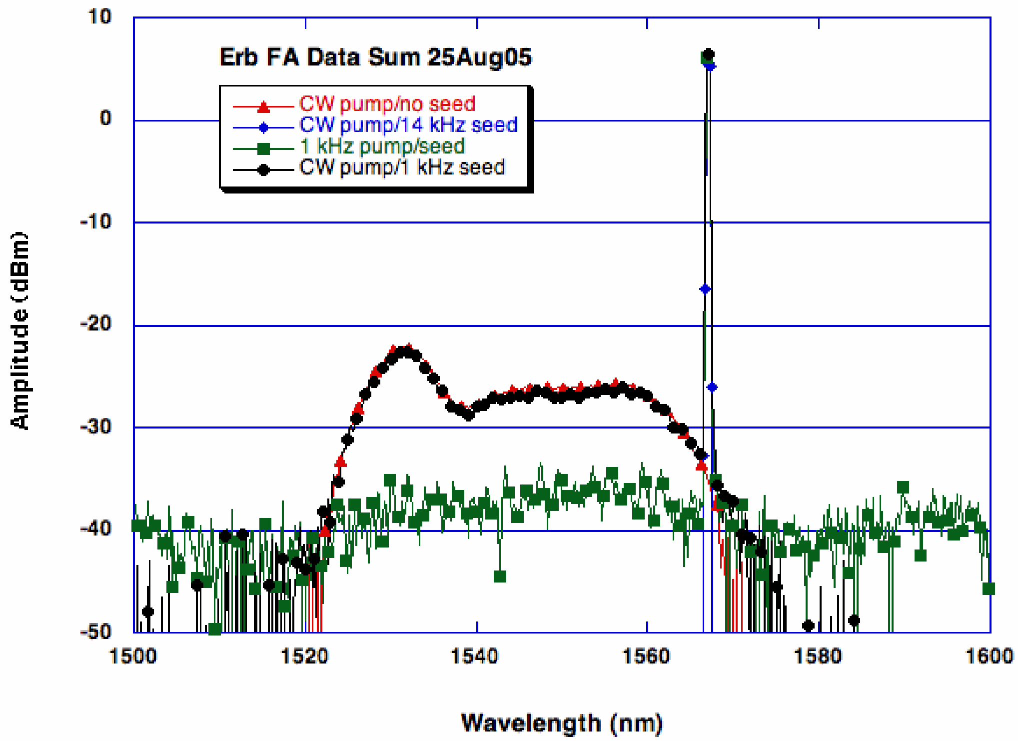
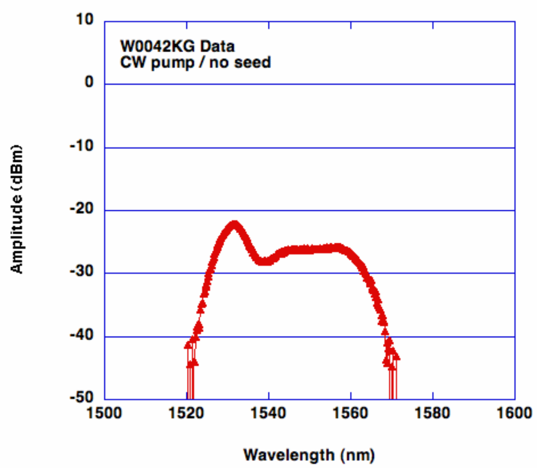
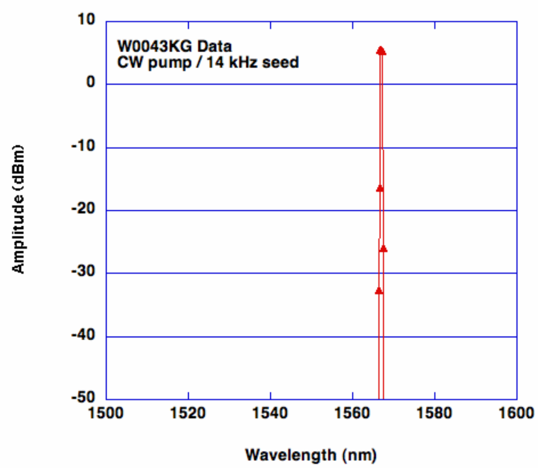


Figure 6. Summary of first stage Er^{+3} doped fiber amp output with varying pump & seed conditions. ASE suppression is noted in the 1kHz pump/seed curve.





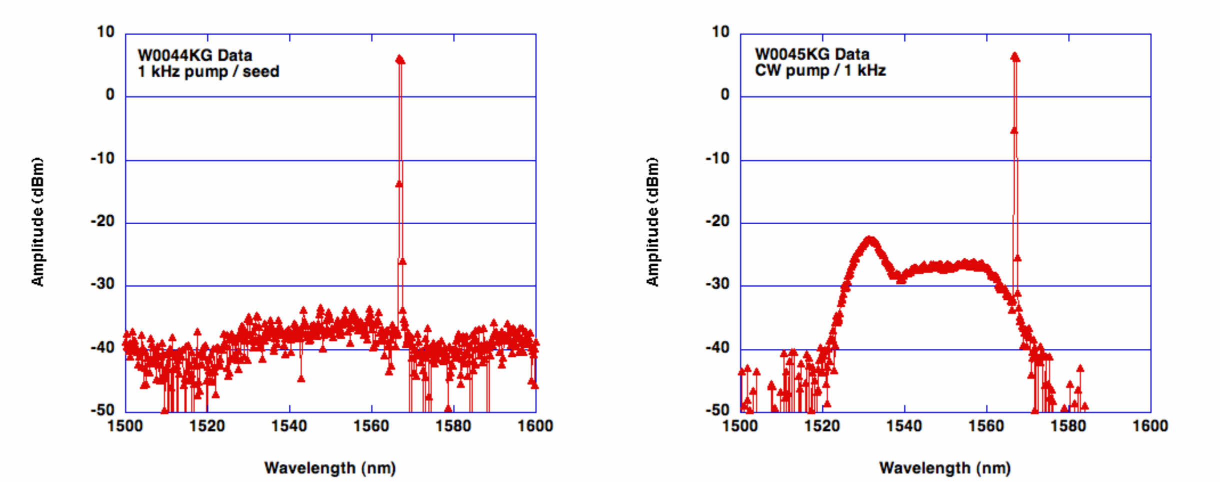


Figure 7. Optical spectrum from 5% tap on single stage Erbium fiber amp with both CW & pulsed pumping.

Figures 6 & 7 show the output optical spectrum of the first stage Erbium doped fiber amp as seen through a 5% tap between the first and second stages. The upper left plot shows the amplified spontaneous emission when CW pumping the gain fiber without a seed signal. The upper right plot shows the amplified pulsed seed signal, under CW pumping. The seed is being directly modulated with a 1 µsec pulse and a 70 µsec pulse repetition period (PRF = 14.28 kHz). Notice the ASE has been completely suppressed under these operating conditions. The lower left plot shows the output spectrum when the pump laser and seed laser are pulsed at 1 kHz. The pump diodes are pulsed with a 190 µsec pulse and the seed is driven with a 1 µsec pulse near the end of the pump pulse (189 µsec). This enables the fiber to become energized, i.e. Erbium ion population becomes inverted, before the seed pulse sweeps out the gain. If the pump lasers are returned to CW operation, the result is seen in the lower right plot. With the seed still pulsing with 1 µsec pulses at 1 kHz, the ASE begins to build up reducing the fidelity (i.e. signal to noise or extinction ratio) of the output. Two important things to notice, the peak signal output power (~6 dBm) does not change with the changing pump conditions and the ASE is suppressed an additional 10-15 dB by pulse pumping. Further, pulse pumping (lower left) reduced the power consumption by 80% over the CW pumped amplifier.

2. Ytterbium Doped Amplifier Development

A single stage CW fiber amplifier was developed using single mode, Ytterbium doped gain fiber and co-propagting pump diodes. A 100 mW diode laser from Lumics (Germany) was used to seed the amplifier while 150 mW FBG stabilized diode lasers were used to optically pump the amplifier. The seed characteristics, optical power vs. current and optical spectrum, are shown in Figure 8.

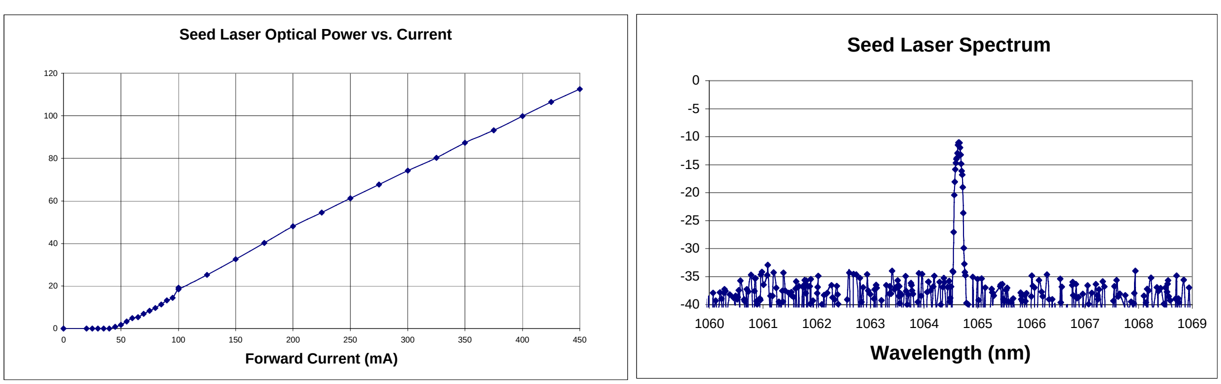


Figure 8. Power vs current and optical spectrum of the seed laser for the Yb doped fiber amplifier.

The components were assembled using fusion splicing techniques and the block diagram is shown in Figure 9.

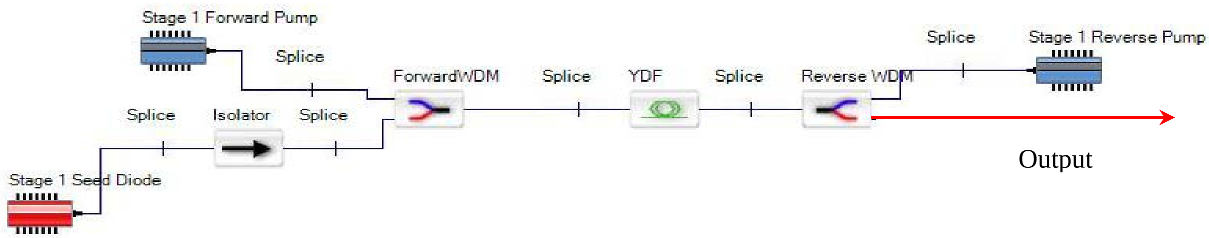


Figure 9. Block diagram of the Yb doped fiber amp.

The performance of the single stage amplifier was modeled using a vendor supplied application designer. CW performance of the amplifier was recorded and compared to the model, results are shown in Figure 10. The observed output power, ~16 dBm, was significantly less than the predicted performance of 26 dBm and is likely due to the known problem of photo-darkening within the fiber. New fiber, with a lower Yb^{+3} doping density, has been acquired that is reportedly less sensitive to this effect. Pulsed operation and testing will begin once a suitable pulsed laser diode driver is developed for the seed laser. Pulse pumped diode drivers designed and tested for the Er doped fiber amp will be used for the pulse-pumped Yb amplifier development.

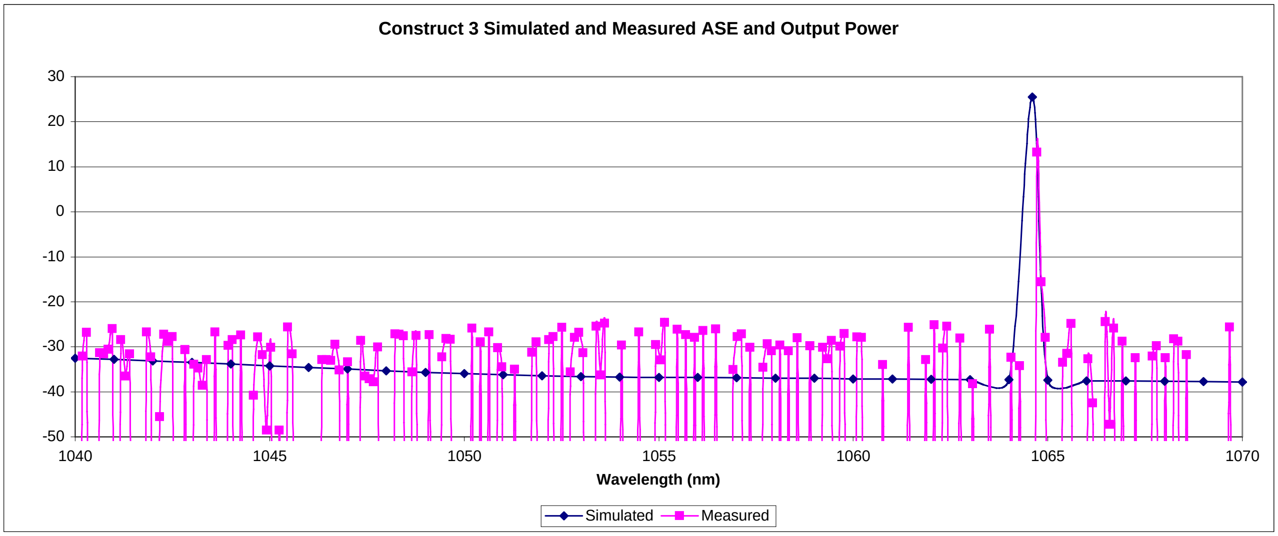


Figure 10. Comparison of simulated performance to experimental results of Yb doped fiber amplifier.

3. Frequency Doubling

Frequency doubling using periodically-poled non-linear crystals, e.g. PPKTP and lithium-niobate will take place once the second stage amplifiers have been added and their performance modeled and experimentally measured. We expect good doubling efficiency due to the high peak powers we anticipate from the two stage amplifiers.

CONCLUSIONS & FUTURE WORK

The results of the Er doped amplifier development have demonstrated the efficacy of pulse pumping under certain operational regimes, i.e. those regimes where the PRF is below the maximally efficient PRF for a CW pumped system, particularly low PRF and low duty cycle scenarios. Dramatic improvements in overall efficiency and suppression of ASE were realized by pulse pumping the amplifiers. Work continues on the Yb amplifier development and we expect greatly improved results with the replacement gain fiber and the addition of optical isolators on each of the pump legs. Further, pulsed performance of the Yb amp should easily exceed that of the Er amp shown here due to the much higher seed power available from the Lumics seed laser. Second stage fiber amplifiers using large mode area (LMA) Yb and Er doped fibers will be added to the existing first stage amplifiers to increase the peak output power. We are currently modeling the first stage amplifiers and expect greater than 20 dB of gain from the second stage amplifiers, yielding pulse powers of 2 kW or more and pulse energies from 20-200 uJ depending on the pulse width. Frequency doubling with periodically poled KTP will begin on the Erbium doped fiber amp after the two-stage amplifier is modeled and characterized.

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