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High Average Power, High Energy Short Pulse Fiber Laser System

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FY06 LDRD Final Report
High Average Power, High Energy Short Pulse Fiber Laser System
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Michael J. Messerly, Principal Investigator

Abstract

Recently continuous wave fiber laser systems with output powers in excess of 500W with good beam quality have been demonstrated [1]. High energy, ultrafast, chirped pulsed fiber laser systems have achieved record output energies of 1mJ [2]. However, these high-energy systems have not been scaled beyond a few watts of average output power. Fiber laser systems are attractive for many applications because they offer the promise of high efficiency, compact, robust systems that are turn key.

Applications such as cutting, drilling and materials processing, front end systems for high energy pulsed lasers (such as petawatts) and laser based sources of high spatial coherence, high flux x-rays all require high energy short pulses and two of the three of these applications also require high average power.

The challenge in creating a high energy chirped pulse fiber laser system is to find a way to scale the output energy while avoiding nonlinear effects and maintaining good beam quality in the amplifier fiber. To this end, our 3-year LDRD program sought to demonstrate a high energy, high average power fiber laser system. This work included exploring designs of large mode area optical fiber amplifiers for high energy systems as well as understanding the issues associated chirped pulse amplification in optical fiber amplifier systems.

Introduction/Background

In order to focus our research on technology appropriate to applications of interest to DOE, we propose to design and construct a high average power, high-energy short pulse fiber laser system. Based on initial work performed here at LLNL and reported works in the literature [2, 3], we believe that systems with the following characteristics can be constructed in an all fiber format.

1) <1ps pulse width
2) 1mJ pulse energy
3) 100kHz repetition rate
4) 100W average power
5) Compact size (<1m^3)
6) Minimal utilities (208V, 40A, LCW cooling)

We propose a system block diagram such as that shown in figure 1 below.

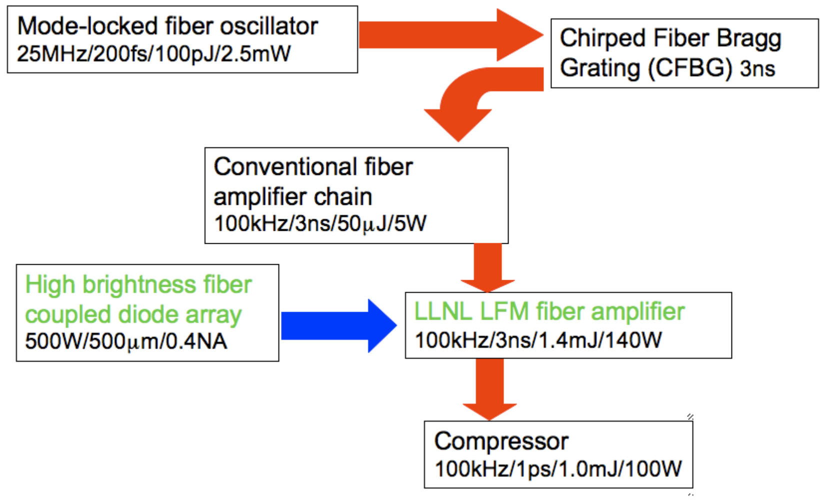


Figure 1: Block diagram of fiber system.

The block diagram above outlines the technical plan we pursued for achieving the ultimate research goals. Pulses from a mode-locked fiber oscillator are selected, stretched in a chirped fiber Bragg grating, amplified in a standard fiber pre-amplifier similar to those found in NIF, further down selected and then amplified in final set of high energy large flattened mode fiber amplifiers and compressed.

The research associated with constructing a system such as this is two fold, understanding how to make a large mode area optical fiber and understanding how to do chirped pulse amplification in an optical fiber amplifier system. In the course of our work we made significant strides in understanding both of these goals. Regrettably, the program was never funded at a level that would permit us to purchase the 2kW high brightness fiber coupled diode laser array shown in figure 1. Thus >100W average power levels were not achieved. Significant work was however done in understanding high energy fiber amplifiers at lower average power and understanding chirped pulse amplification in optical fiber amplifier systems.

Research Activities, Results and Technical Outcome

Part 1: Understanding large mode area optical fiber amplifiers.

The large flattened mode (LFM) fiber amplifier was developed at LLNL [4, 5, 6]. It distributes the intensity of the mode evenly across the fiber via a specialty refractive index core design. This even distribution of intensity across the core permits greater output pulse energy prior to the onset of stimulated Raman scattering (SRS). Figure 2 below details the radial LFM refractive index profile and the standard step index core profile and their associated radial intensity distributions in the core of the fiber.

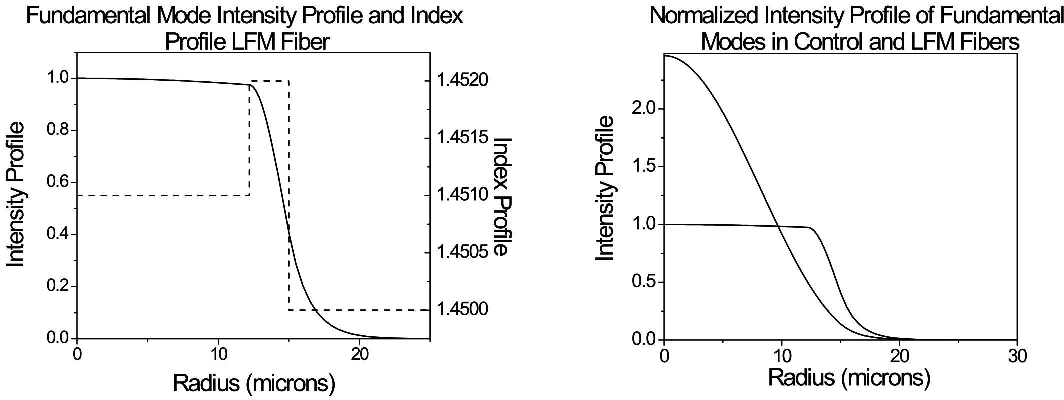


Figure 2: Left: refractive index profile and preferred mode of LFM fiber. Right: comparison of the intensity profiles of a step index fiber and an LFM fiber with the same total power.

SRS was previously shown in the literature to be the limiting factor in scaling the output energy of fiber lasers [2]. In our initial work, we purchased a control fiber with a standard step index, large mode area core and an LFM fiber with an equivalent core size. We were able to demonstrate a change in the onset of SRS between the LFM fiber and the control fiber for similar fiber lengths, input pulses, amplification and pulse energy. The data from this initial concept experiment is shown in figure 3 below.

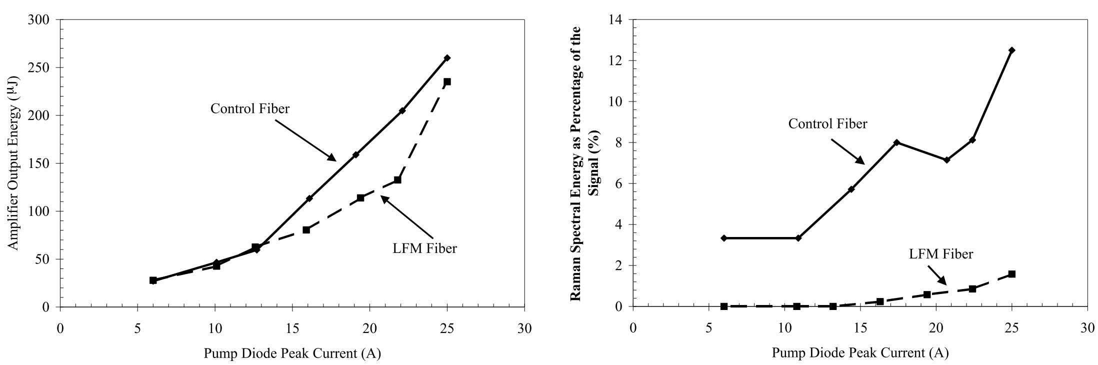
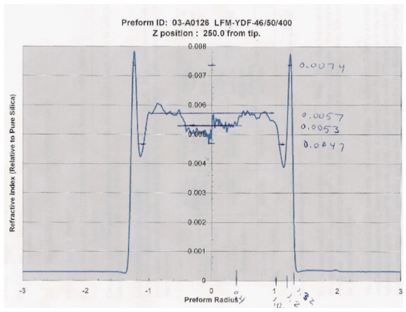


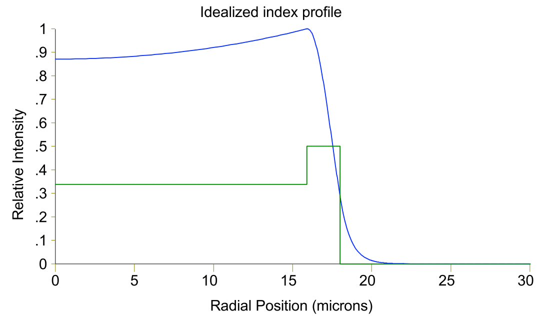
Figure 3: Left: output energy vs. pump diode current for the step index control fiber and the LFM fiber. Right: Raman peak spectral power as a function of the pump diode current for the same fibers.

This data demonstrates the basic concept that the LFM fiber design is superior for high pulse energy applications. However, there remain significant research hurdles in obtaining output energies greater than 10mJ, while maintaining good beam quality with pulses that can be compressed back to <1ps. We believe these hurdles can be overcome, as "back of the envelope" calculations all indicate that the scaling to these output energies are feasible.

We conducted an extensive design study of the LFM fiber parameter space. We generated a specification for the fiber in consultation with the fiber manufacturer to maximize the manufacturing tolerances for the fiber design. A first iteration fiber was produced and received. Initial testing showed excellent agreement with the expected beam profile (figure 4)



(a)



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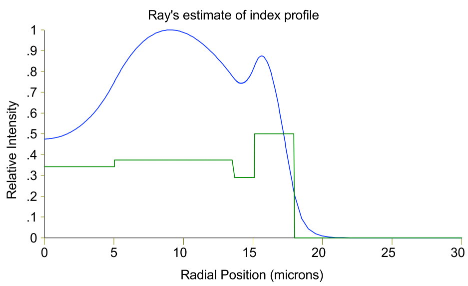

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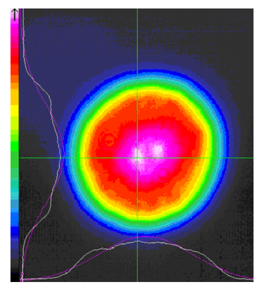


(d)

Figure 4: (a) preform refractive index profile from fiber perform, (b) idealized step index profile and expected mode, (c) expected mode accounting for some non-ideal waveguide features, (d) measured light from LFM fiber imaged onto a digital camera.

We were quite pleased with the quality of the LFM fiber mode. However, there was a manufacturing issue with the fiber as initially received. Namely the concentration of the rare earth ion providing the laser gain (Yb^{3+}) was too high. This resulted in an undesirable combination of concentration quenching and photo-darkening of the fiber, which rendered the fiber unusable for gain measurements.

We attempted to repeat the above fiber with lower Yb^{3+} concentration. However, due to a second manufacturing error, this fiber came in with a numerical aperture that was too high. This effect of a high numerical aperture is to allow many optical fiber modes to propagate in the core simultaneously. With a low numerical aperture optical fiber it is possible to use bend induced losses to attenuate higher order modes leaving only the desired fundamental mode. However, the numerical aperture of this second fiber was too high to allow us to use this technique. As a result it was not possible to achieve effective single mode operation and the result was very poor beam quality.

While we were working on this a second research group at an outside company, Fibertek, became interested in this fiber design and was pursuing work on their own towards a large effective area LFM fiber. We realized we needed to make a third iteration of the fiber with tighter controls on the index profile. Intriguingly they were in almost the same position as we were in this regard. In the course of discussions with them, we decided to pool our resources for a final LFM fiber attempt with a 50μm core diameter and a target effective mode area greater than 2000μm^2. It was realized at this point that the LFM mode at the cusp of the design space between an mode that was annular or donut like and the traditional Gaussian fundamental mode. By joint agreement we targeted a mode that was just to the Gaussian side of the ideal LFM mode. The goal here was that even if the fiber were not perfect it would still have reasonably good beam quality. It was beginning to be realized at this point that the LFM fiber design was on the edge of the manufacturing tolerances achievable by conventional modified chemical vapor deposition (MCVD) fiber manufacturing processes combined with solution doping to allow rare earth doped fiber cores. Specifically, the rare earth doping process appeared to be creating larger than anticipated variations in the fiber refractive index profiles and this was having a negative impact on our ability to construct the desired fiber waveguide. Nevertheless, we proceeded with a final attempt a constructing the target optical fiber.

The resulting fiber from the above efforts permitted us to get close to our original technical goals. Specifically, a 1.9m piece of the 50μm LFM fiber produced 1mJ pulses at 10kHz repetition rate for 10W of average power with minimal impact on the spectra. Figure 5 below shows the output spectra from the 10W average power experiment on both a linear and logarithmic scale.

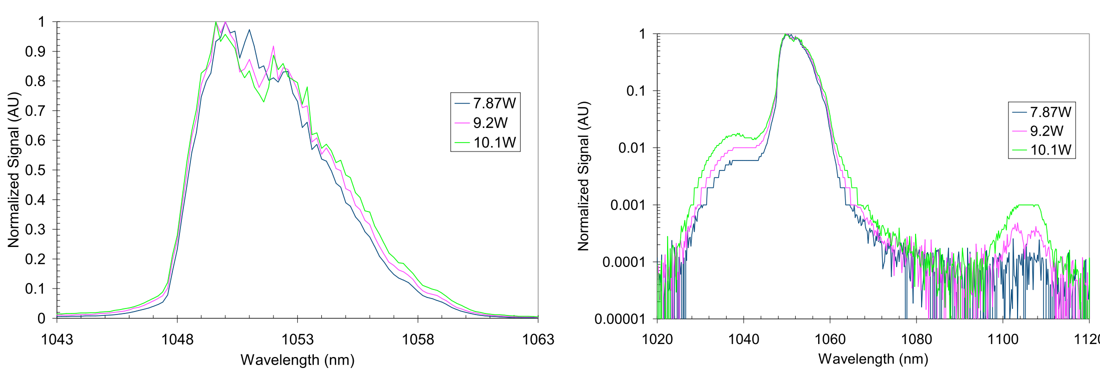


Figure 5: Spectra from 1.9m LFM fiber amplifier (NuFern LFM-YDF-45/49/250). Launched pump power was approximately 80W and input signal power was approximately 2μJ or about 20mW at 10kHz. The pulse width in time was 1.2ns.

The pulses injected into the LFM amplifier in figure 5 above originated in a mode-locked oscillator and had been stretched using a conventional grating based bulk stretcher and amplified in conventional fiber amplifiers prior to injection into the LFM amplifier. The injection system will be discussed in greater detail in the next section. In figure 5 above, we see that the pulse spectrum is essentially unchanged by the amplification process. As the pulse energy approaches 1mJ, we begin to see a hint of stimulated Raman scattering (SRS) in the spectra at the 0.001 level relative to the peak of the pulse, indicating that if we had more pump power we might be able to get slightly higher pulse energy prior to the onset of detrimental non-linear effects. We also looked at a control fiber in this amplifier configuration in which the control fiber had a standard step index core with a 30μm core diameter with the same length, injected signal pulses and pump power. This fiber only reached a pulse energy of about 100μJ prior to the onset of quite significant and impressive non-linear effects. Specifically, not only did the system generate an SRS signal, but it also began to generate red and blue light, that was visible to the naked eye. Some representative spectra are shown in figure 6 below.

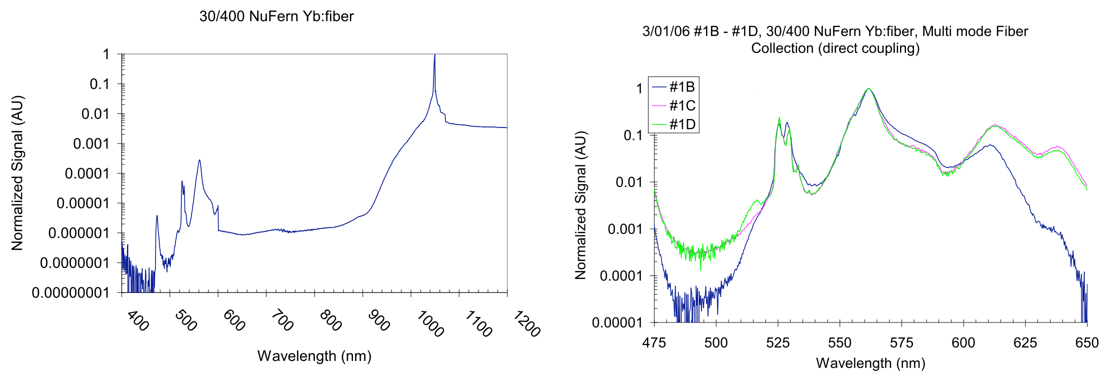


Figure 6: Example of extreme non-linear effects in 30μm step index core fiber at >100μJ output pulse energy.

While the LFM fiber results at 1mJ appeared promising, the outstanding question was one of beam quality. The fiber appeared to guide a single mode, which was not quite LFM mode, but more of a donut or annular shape. This mode had a measured M^2 of 4, which was much higher than desired. Nevertheless, we were able to focus the beam at 10W/1mJ quite tightly and were able to show that we could achieve dielectric breakdown of air. That is the focused laser beam formed a plasma ball in free space as seen in figure 7 below.

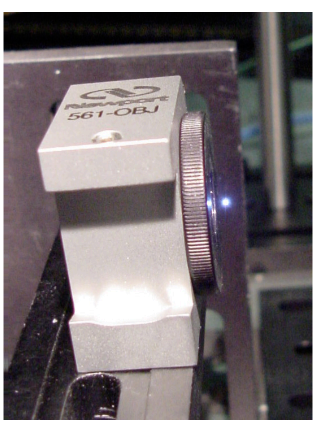


Figure 7: Focused 10W, 10kHz, 1mJ/pulse fiber laser beam. The bright spot behind the lens is a ball of plasma formed in the air through dielectric breakdown. This occurs at 10^{10} W/cm^2.

Despite the relative success of the LFM fiber our current belief is that this is not a promising means for increasing the aperture of optical fiber modes. Based on extensive theoretical and as a result of this work experimental studies, our belief is that MCVD fiber fabrication techniques lack the refractive index control needed to achieve core diameters larger than 30μm with good beam quality. Others have reported larger cores in photonic crystal based fiber and we have in fact obtained a polarizing photonic crystal fiber from a vendor with a 41μm core diameter that demonstrated good beam quality. The photonic crystal manufacturer achieves the required refractive index control through a laborious process of creating the core material as a rod and then pulling it into cane, stacking the cane segments back into a single perform and then pulling the segments into cane. Repetition of this process eventually leads to a uniform core material, which can then be used to create high quality large diameter fiber waveguides. However, this process can take months of real time to get to the required index control. We have other concepts we believe can create large fiber waveguide apertures, but do not have time to delve into them in this report. As a result of our extensive investigations we settled on using the Crystal Fibre 41μm core polarizing fiber as the amplifier for our laser system demonstration. Due to the smaller core over the LFM fiber, we were limited to about 200μJ of output pulse energy from the system with this fiber.

Part 2: Systems level testing and evaluations.

Over the course of our three year experiment we examined a number of systems. We will detail only the one we investigated in the most detail here. This system was the initially proposed chirped fiber Bragg grating (CFBG) as a stretcher. This system worked well at low energy and average power. However the only CFBG we were able to obtain created dispersed pulses that had to be recompressed with a 1480g/mm grating. Our only 1480g/mm grating was gold coated and thus limited in average power and pulse energy. A second system used a stretcher based on a 1780g/mm multilayer dielectric grating. This stretcher was designed with off-axis cylindrical mirrors to compensate for the material dispersion of the fiber. The pulses from this stretcher could be recompressed with a 1780g/mm multilayer dielectric grating and thus could be taken to higher average power and pulse energy. However, due to lack of time and funding the stretcher design was never optimized and this limited our pulse quality and the amount of bandwidth we could get through our system. We believe we now understand those issues better, but ran out of time to implement them during the course of the program. Nevertheless, pulse energies up to 100μJ at 5kHz were obtained showing the overall promise of the system. However, a full characterization of the system and the output pulse quality was not completed due to lack of time.

The system employing the CFBG is shown in figure 8 below. The seed source for the system is a mode-locked fiber laser based on the design popularized by a group at Cornell University [7]. This oscillator produced 24mW output power at a pulse repetition rate of 35MHz or about 0.7nJ pulses. These pulses had 30nm of bandwidth and could be dechirped to less than 100fs. The pulses were amplified in a compressed pulse amplifier which consisted of 4m of 20μm core double clad Yb^{3+} fiber. The output of this amplifier was 192mW or about 5.5nJ/pulse. These pulses were sent through an AOM, which could be used to select single pulses reducing the repetition rate of the system and thus increasing the energy per pulse. However, for the initial low energy experiment, they were turned on without modulation and simply passed the pulses with no change in repetition rate. The pulses were then bounced off the CFBG using a Faraday optical circulator configuration. This system reflected about 11.2mW of the incident power. The CFBG had a 50% reflection coefficient, an 8nm bandwidth (so significant power was lost outside the spectra) and significant coupling loss into the fiber from the AOM deflected beam. The 11.2mW stretched pulses had a pulse width of about 1.4ns and a pulse energy of 0.32nJ. The measured CFBG GDD was 106ps^2/rad and the TOD was -1.4ps^3/rad^2, with significant error likely in the TOD measurement due to its low value. Another 20μm core cladding pumped Yb^{3+} fiber amplifier boosted the signal energy to 385mW or about 11nJ. Another AOM was inserted to allow for ASE reduction between pulses in the lowered repetition rate case, but again this was set-up to simply allow pulses to pass unmodified for the first experiment. A final 30μm core cladding pumped Yb^{3+} fiber amplifier boosted the signal to 608mW or 17nJ per pulse. These pulses were recompressed with a 1474g/mm gold grating at 47.5 degrees angle of incidence in a classical Traecy compressor configuration. 221mW of transmitted power was sent to a background free auto-correlator to enable analysis of the pulses.

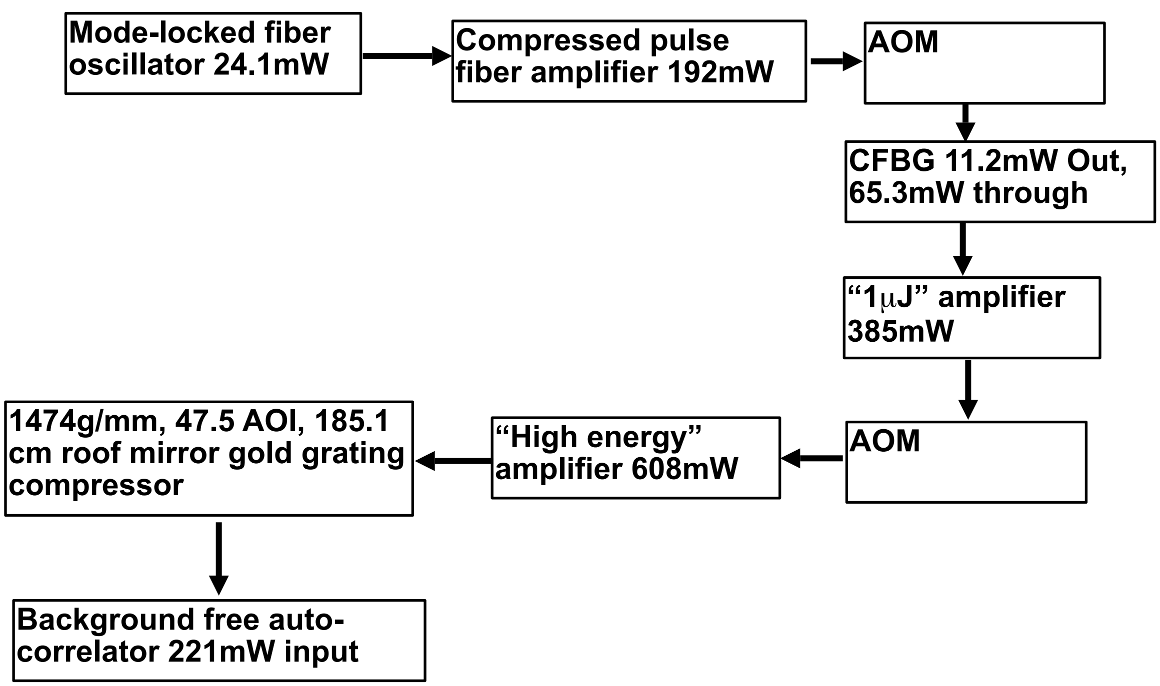


Figure 8: CFBG based chirped pulse amplification system.

The auto-correlator results are shown in figure 9 below on both a linear and logarithmic scale. The auto-correlations show a reasonably good pulse with a small pedestal that is likely due to minor reflections somewhere in the overall system. The auto-correlations also look quite good down to the 10^{-6} level relative to the peak of the pulse. In figure 10 below, we show the spectrum at the output of the system as well as the auto-correlation again with a theoretical calculation of the measured spectrum Fourier transformed and assuming a flat phase front. We see from figure 10 that most of the auto-correlation is explainable from the shape of the spectrum, with the exception of the small bumps that are likely satellite pulses. The main peak of the pulse is close to transform limited.

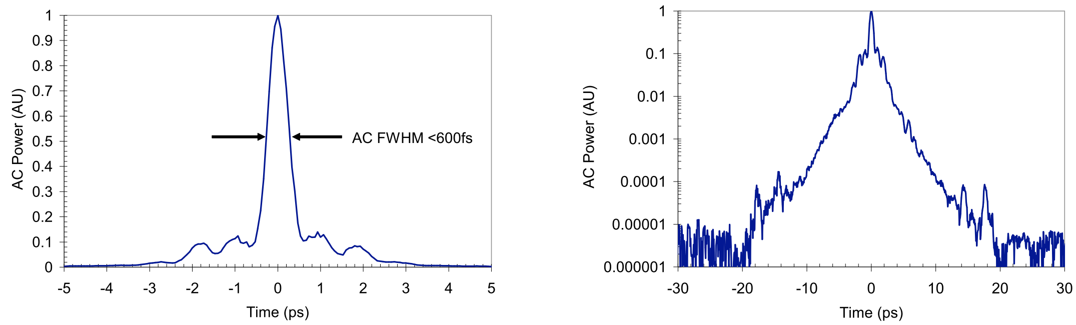


Figure 9: Auto-correlations from system in figure 8.

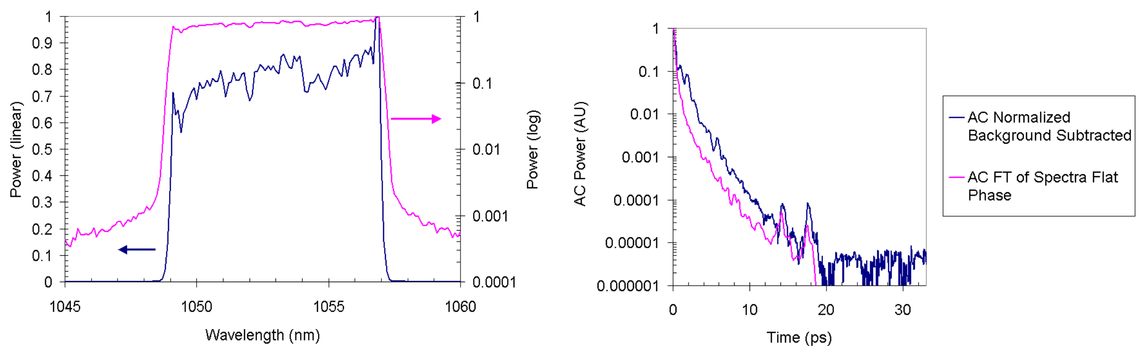


Figure 10: System spectra and auto-correlation again along with the expected auto-correlation based on the spectrum.

Given the successful recompressions with the above system, we proceeded to increase the pulse energy. As a part of the effort to scale up the pulse energy, we removed the compressed pulse amplifier from the system. It was our belief at that point in time that it was not making actually improving the system performance and we would be better off without the added complexity. There had originally been a plan to include an amplified spontaneous emission pulse cleaner after the compressed pulse amplifier in order to improve the overall system pulse contrast. However, based upon the experiments at low energy, this was determined to be unnecessary. To that end, we proceeded to ramp up the pulse energy using the system outlined in figure 11 below. One can see from the diagram that the system is essentially the same as that detailed above in figure 8 except for the compressed pulse amplifier. The same compressor and background free auto-correlator were used in this system as in figure 8, although they are not shown explicitly in figure 11.

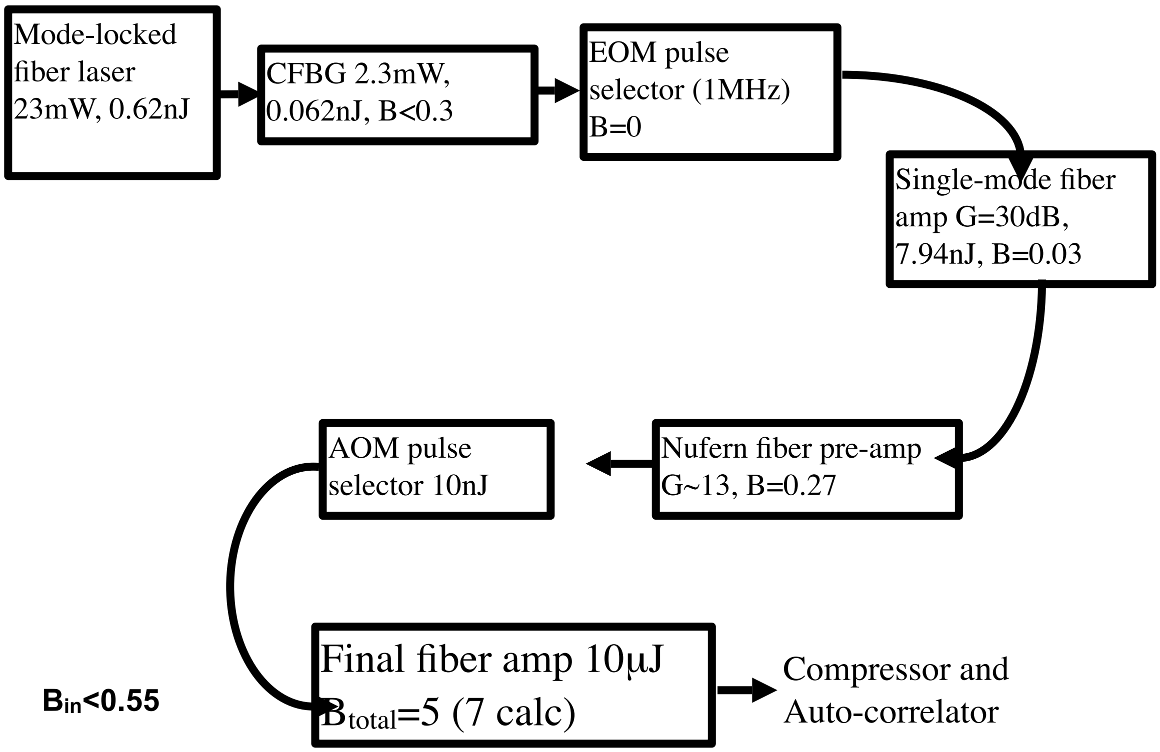
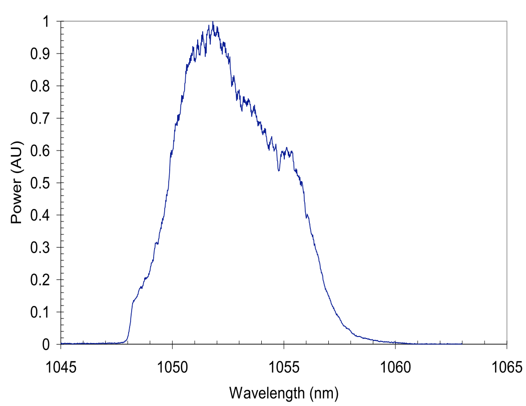


Figure 11: Fiber laser system employed to examine scaling of pulse energy.

The spectrum, auto-correlation and theoretical fit to the auto-correlation are shown in figure 12 below for the case of 10μJ pulses.



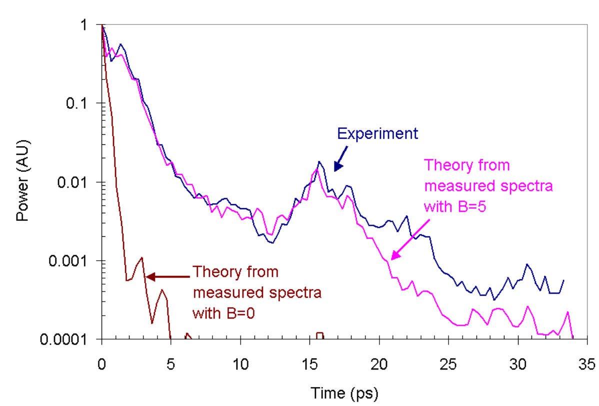


Figure 12: Data from system in figure 11 at 10μJ output pulse energy.

We see from figure 12 that the measured auto-correlation was consistent with the Fourier transform of the measured spectra, once the effect of B-integral on the chirped pulses is taken into account. Given the length of our final amplifier in this case, we achieve a significant B-integral of 5 even at low pulse energies. This is because our better amplifiers were not yet available at this point in time. With this large of a non-linearity on the chirped pulse it was not possible to get a good pulse recompression even at low energy. We believe this to be due to the effect of amplifier gain tilt on the spectrum. If the spectrum could be kept smooth and flat an improved pulse recompression should be possible. Further an amplifier re-design was needed in order to keep the accumulated B-integral at least this low at higher energies. We would also like to have a longer stretch and have a compressor that was compatible with 1780g/mm multi-layer dielectric gratings. We began work on a bulk stretcher based on off-axis cylindrical mirrors, but the program ran out of time and funding before it could be completed.

Exit Plan

This work has been invaluable as background in understanding the design requirements for the fiber laser front end for the Advanced Radiographic Capability (ARC) on the National Ignition Facility (NIF). Thus to a large extent it has been picked up by the NIF directorate to further the NIF mission and goals. We are also developing proposals to use systems similar to what we have described here to drive laser based, high brightness and high average power X-ray sources. These sources would permit laboratory scale instruments that could enable new applications in radiography.

Summary

We investigated a novel fiber design to reduce non-linearities. The design showed some promise. However, manufacturing tolerances in fiber manufacture limited the full benefits. Nevertheless the idea was found to be quite intriguing and several groups picked up on it and advanced the work [8,9]. The investigation of the concept also led us to a much deeper understanding of the ultimate scalability of the mode area of an optical fiber. We are working on a research publication that will discuss this in detail.

We also investigated high average power and high energy chirped pulse fiber amplification systems. This work has been invaluable as background in understanding the design requirements for the fiber laser front end for the Advanced Radiographic Capability (ARC) on the National Ignition Facility (NIF). The most valuable information being that related to the chirped fiber Bragg gratings (CFBG) and the interaction of the CFBG with self phase modulation on the chirped pulses. Finally, we also investigated the use of a bulk stretcher and compressor. While this work was not fully completed we believe we learned enough that a follow on program would have a significant head start and much higher probability of success.

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