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ABSTRACT

We are developing an all fiber laser system optimized for providing input pulses for short pulse (1-10ps), high energy (~1kJ) glass laser systems. Fiber lasers are ideal solutions for these systems as they are highly reliable and once constructed they can be operated with ease. Furthermore, they offer an additional benefit of significantly reduced footprint. In most labs containing equivalent bulk laser systems, the system occupies two 4'x8' tables and would consist of 10's if not a 100 of optics which would need to be individually aligned and maintained. The design requirements for this application are very different those commonly seen in fiber lasers. High energy lasers often have low repetition rates (as low as one pulse every few hours) and thus high average power and efficiency are of little practical value. What is of high value is pulse energy, high signal to noise ratio (expressed as pre-pulse contrast), good beam quality, consistent output parameters and timing. Our system focuses on maximizing these parameters sometimes at the expense of efficient operation or average power. Our prototype system consists of a mode-locked fiber laser, a compressed pulse fiber amplifier, a "pulse cleaner", a chirped fiber Bragg grating, pulse selectors, a transport fiber system and a large flattened mode fiber amplifier. In our talk we will review the system in detail and present theoretical and experimental studies of critical components. We will also present experimental results from the integrated system.

Keywords: Short pulse lasers, fiber lasers, laser front ends

1. INTRODUCTION

Nd: Glass lasers such as Lawrence Livermore National Laboratory's National Ignition Facility (NIF), the University of Rochester's Omega Laser and France's MegaJoule laser are capable of producing laser beams with multiple kilojoules of laser energy in a pulse from a single beam line [1]. Typically these lasers are run in a "long-pulse" mode with pulses on the order of 1-10ns creating peak powers on the order of 10^{12}W. However, it is also possible to run these lasers in a chirped pulse amplification (CPA) mode [2] and generate high energy (~500J) short pulses (~500fs) and create peak powers on the order of 10^{15}W. Peak powers of this magnitude enable the investigation of new physics phenomena in the relativistic optics realm enabling the laser-based production of x-rays for diagnostics and possibly new capabilities for inertial confinement fusion experiments such as fast ignition.

Fiber lasers offer unique benefits as front ends for large Nd:Glass laser systems. Fiber lasers are compact and the critical components can be rack-mounted. The systems are efficient using minimal electrical power and cooling water compared to previous systems based on optical parametric amplifiers, Nd:glass or Ti:Sapphire. As demonstrated by the telecom industry these laser systems can be engineered for a high degree of robustness, reliability and ease of use. They are also generally quite safe as they are all solid state devices with the light beam completely contained within the fiber waveguide. As such NIF has adopted an Yb^{3+} based fiber laser front end for its long-pulse laser function [3].

However, the technology for a short-pulse fiber front end laser for a Nd:Glass petawatt class laser systems has not yet been developed. The requirements for such a system are unique and differ significantly from the requirements one normally considers short pulse fiber laser systems. One interesting feature is that high average power (typically a key advantage of fiber laser systems) has little value for Nd:Glass laser front ends as these systems typically only fire one laser pulse every 4-8 hours in order to allow time for the glass to re-achieve thermal equilibrium between shots. Typical requirements for a front end system are 1053nm center wavelength, ~4nm bandwidth (this is still large compared to the Nd:glass amplification bandwidth {~2.2nm}), the ability to control the dispersion to generate final pulse widths in the 1-10ps range (the compressor for a 1kJ class laser is typically quite large and difficult to adjust so adjustments are preferred to be made in the front end) and up to 300μJ pulse energy. An additional requirement is an extremely stringent pre-pulse contrast requirement of the order of 10^8. This is because with the final beam tightly focused an ASE pedestal that is higher than this will ionize the target prior to the arrival of the main pulse and in many cases interfere with the experiment being performed. Another important requirement is a high degree of energy and temporal stability. Energy stability is needed because these systems are operated close to many damage thresholds and too large a pulse could damage expensive optics. Temporal stability is needed in a system like NIF in order to time the arrival of the short pulse with other long pulses, which is required for many experiments. As an example, when completed NIF will have 192 independent beam lines with pulses needing to be timed for arrival at the target with an accuracy on the order of 10ps.

The system we are considering as a short pulse front end for these lasers is shown schematically in figure 1 below.

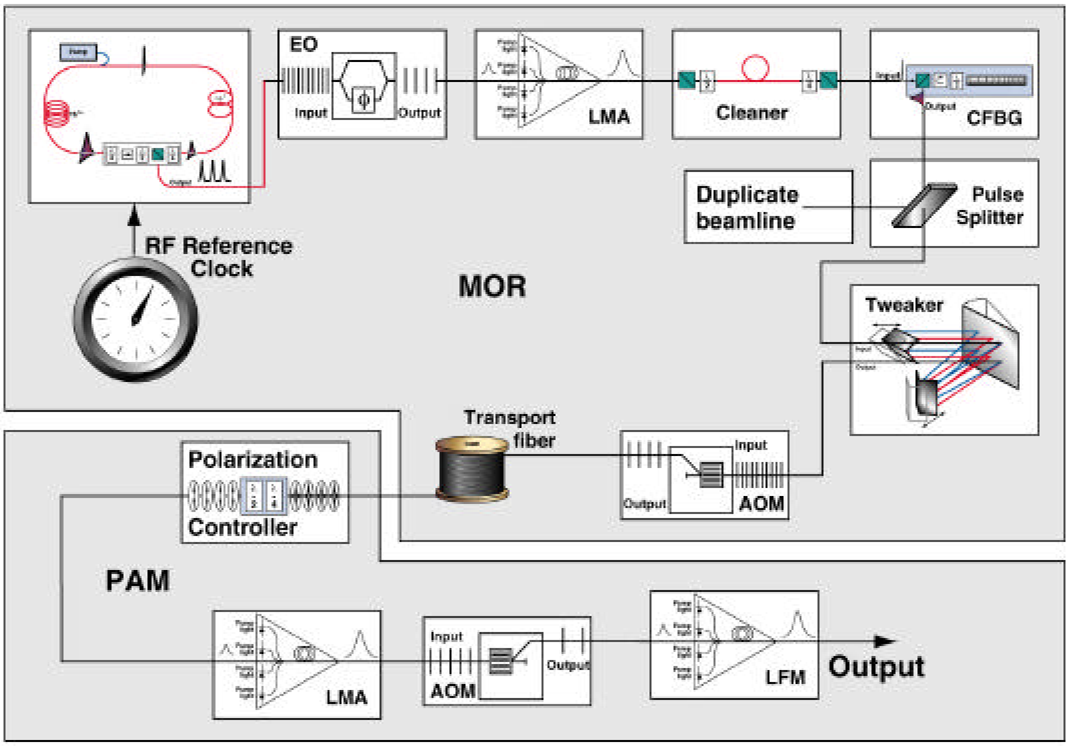

Figure 1: Schematic of a planned prototype fiber front end system for a large Nd:glass laser.

In the system we are considering the pulses are generated in a high energy, mode-locked fiber ring laser [4], which would be phase locked to a reference clock. An electro-optic modulator would be used to drop the repetition rate of the pulse train down so as to minimize the amount of average power in the rest of the system. The pulse train is then amplified in a large mode area (LMA) fiber amplifier up to the 50-100nJ level. At this point the pulses, which are slightly chirped exiting the oscillator and chirped more by the compressed pulse amplifier would be recompressed with a small pair of parallel gratings and then "cleaned" in an ASE pulse cleaner. This device uses non-linear polarization rotation to significantly reduce any ASE pedestal accumulated to the point. The pulse is then sent to a chirped fiber Bragg grating (CFBG) for stretching to 1-3ns. Depending on the energy of the pulses at this point, a pre-stretcher may be employed to reduce self phase modulation in the CFBG to an acceptable level. After the CFBG, the pulses can be split to accommodate multiple beam lines typical in lasers such as NIF or Omega. Typically all beam lines are effectively identical and our schematic tracks only one of these beam lines for clarity. A "tweaker" is then employed to adjust the chirp of the pulses. This tweaker will likely consist of a bulk optic grating with movable roof mirrors to permit a varying dispersion. This is needed to permit the pulse width to be adjusted into the 1-10ps range required for potential experiments and for trimming the dispersion of the rest of the system to compensate for the lack of adjustment in the final system compressor. At this point the repetition rate may be further adjusted if necessary by an acousto-optic modulator. A large mode area single mode transport fiber is employed to carry the pulses from a conveniently located master oscillator room out to the main Nd:Glass laser bay where space is limited. This transport fiber may be up to 100m long and needs to accommodate as much pulse energy as possible without inducing non-linear effects. We have found that up 15nJ can be reasonably transmitted over this distance, while maintaining a conservative margin on non-linearities. In the main laser bay, the polarization is restored with an active polarization controller. A large mode area (LMA) fiber amplifier then amplifies the pulse energy up to 1.2μJ. A final AOM is employed to reduce ASE saturation between the fiber amplifiers and to reduce the repetition rate of the pulse train to 960Hz at this point, if needed. An LMA or a large flattened mode (LFM) final fiber amplifier then boosts the output power of the system to 300μJ for launch into the main Nd:Glass laser chain.

2. COMPONENT REQUIREMENTS AND STUDIES

Master Oscillator

In this section we discuss the component evaluations and investigations we have performed in our effort to study and understand the practical realities facing the deployment of a system such as that described above. A critical component in the system is the master oscillator. In order to study mode-locked fiber lasers we constructed an oscillator based on the configuration in reference 4, which is shown schematically in figure 2 below.

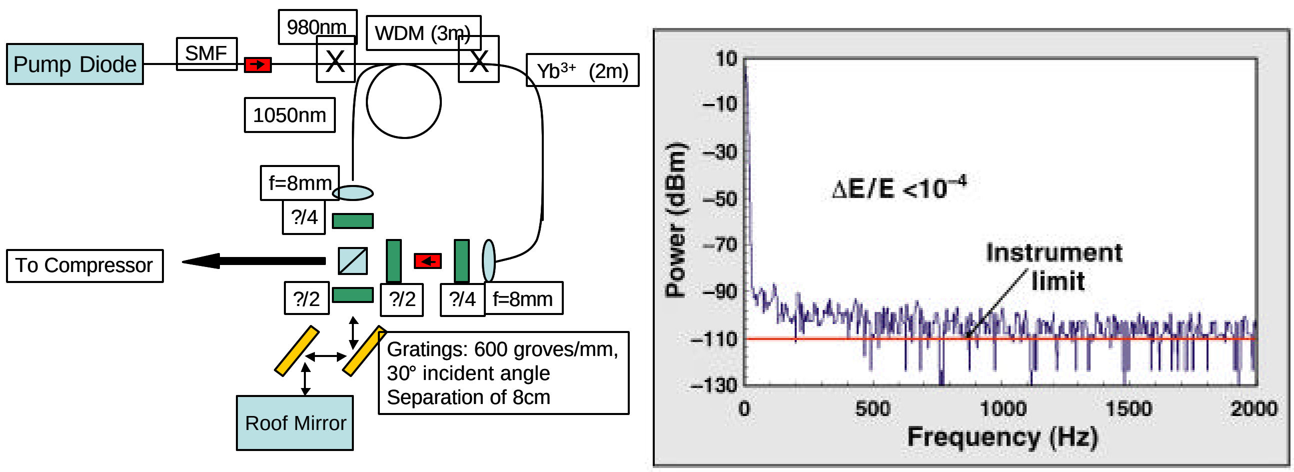

Figure 2: Left hand side is a schematic of the mode-locked fiber laser. Right hand side is a measure of the amplitude stability of the laser output. The laser operated with the following parameters: 1054nm/36MHz/1.75nJ/77fs/61mW.

As described in reference 4 this laser operates based on non-linear polarization rotation in ring cavity configuration. In its current incarnation, compensation of the relatively large fiber dispersion is provided by a pair of parallel 600g/mm gratings with an 8cm separation double passed at a 30-degree angle of incidence. Currently much of the oscillator consists of classical bulk optics and stages and thus many of the fiber advantages are not readily apparent. However, we are working to create this in an all fiber format. In this case it is hoped the bulk gratings can be replaced by dispersion shifted photonic crystal fiber. With the waveplates optimally adjusted this oscillator ran stably with a center wavelength of 1054nm, a bandwidth of 35nm, a repetition rate of 36MHz, a pulse energy of 1.75nJ and an average power of 61mW. The pulses emerging of the output of the fiber laser are positively chirped. One can dechirp the pulses with a double passed pair of parallel 1200g/mm gratings with an angle of incidence of 58 degrees and a separation of 7mm. Measurement of the resulting pulse train via frequency resolved optical gating (FROG) yields a reasonably clean pulse with a 77fs FWHM.

A particular feature of interest to our application is the energy stability of the oscillator. When the pulse train is measured with a fast photo-diode connected to an RF spectrum analyzer one can gain insight into the energy fluctuations of the laser [5]. The results of this measurement are shown in the right hand side of figure 2, the resolution bandwidth of this measurement was 10Hz. We estimate the resulting pulse-to-pulse amplitude stability to be on the order of 0.01%. Measurements of the higher order frequency components show excellent temporal stability of the pulse train also. However, a very noisy vibration or acoustic environment can alter this, as one would expect. The final all-fiber device will be packaged to minimize noise and vibration effects. It will also include a pie zo-electric fiber stretcher to permit locking of the pulse train to an external clock.

ASE Pulse Cleaner and Pre-Pulse Contrast

As noted in the introduction, a particularly stringent requirement for our system is pre-pulse contrast. Several issues impact this specification including quality of the recompressed pulse and leakage of undesired pulses from the oscillator through the pulse selectors and amplified spontaneous emission (ASE). We are most interested in the latter of these and can use a simple formula to estimate the ASE in a laser amplifier [6].

$$P_{ASE} = 2\, n_{sp}\, (G-1)\, h\nu\, \Delta\nu$$

Where P_{ASE} is the predicted ASE power within the bandwidth $\Delta\nu$, n_{sp} is the number of photons per mode at the amplifier input and is about 1.2 for the case of Yb^{3+} in glass, $h\nu$ is the photon energy and G is the gain. The equation for ASE suggests we actually have very little control in the system design to maximize the pre-pulse contrast. In fact the only thing one can really do is inject a clean pulse into the amplifier chain with sufficient energy in the pulse to ensure that when P_{ASE} is computed the recompressed pulse will have the required pre-pulse contrast. This means one would like to clean the compressed pulse to eliminate any pedestal (or at least reduce it an order of magnitude below the pedestal we predict will be induced by the ASE) and then ensure the pulse energy injected into the system is sufficiently large to ensure G is low enough to yield the required pre-pulse contrast. For a large glass laser system where the final output energy will be on the order of 1kJ and the pre-pulse contrast requirement is on the order of 10^8, we need to inject a clean pulse with an energy on the order of 10nJ into the amplifier chain in order to achieve the required pre-pulse contrast in terms of ASE. Due to expected losses in the components this means we will need about 40nJ launched into the CFBG.

An ASE pulse cleaner can be constructed using non-linear polarization rotation. This is the same physical effect that is used in the mode-locked fiber laser to achieve an intensity dependent switch. (see figure 3 below).

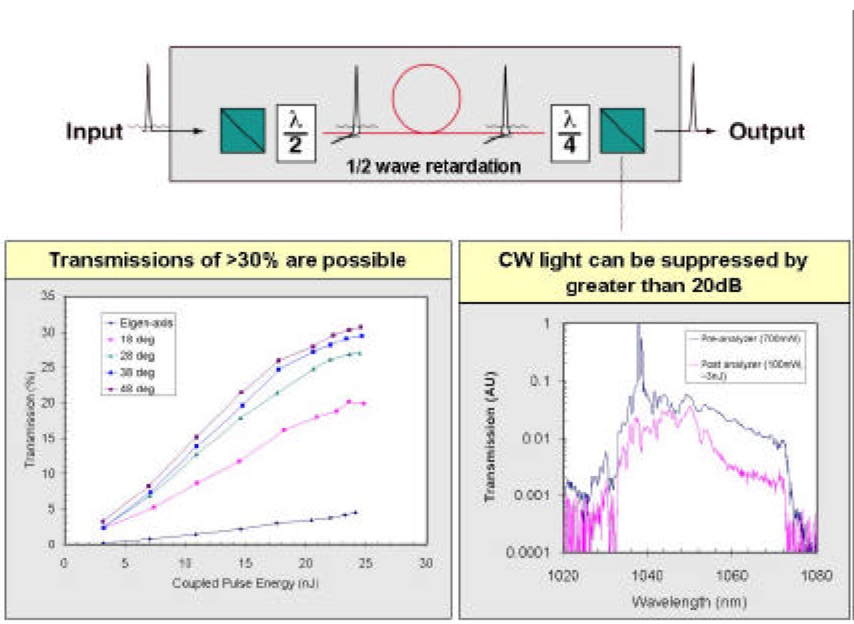

Figure 3: Top: ASE pulse cleaner schematic, bottom left: transmission of ASE pulse cleaner as a function of coupled pulse energy, bottom right: an example of a spectrum with CW breakthrough that had been cleaned.

Referring to the schematic in the top of figure 3, an input pulse is polarized to ensure a pure polarization state. A half wave plate then adjusts the polarization state of the pulse in order to launch it at a specific angle relative to the polarization eigen-axis of the fiber. The pulse is then split into two orthoganally-polarized pulses, which see slightly different path lengths as they traverse the fiber creating an elliptically polarized output pulse. A quarter wave plate is set to compensate for the birefringence of the fiber and the polarization is returned to linear. The output analyzer is then set to completely block the polarized output pulse in the case of very low energy pulses or CW light. When a higher energy pulse is launched into the system the difference in energy of the pulse aligned with the slow axis and the pulse aligned with the fast axis creates a phase shift between the two pulses. The precise mechanism involves both self phase modulation and cross phase modulation and the modeling of this phenomenon is thus somewhat involved [7]. This in turn rotates the polarization state of the light at the output and permits some of the pulse energy to escape through the analyzer. As the pulse energy increases the transmission of the system increases. An example plot of the system transmission as a function of pulse energy is shown at the bottom left of figure 3. In this case, the pulse was slightly chirped with a pulse width of about 7.8ps, the fiber length was 3.5m and the mode field diameter of the fiber was about 12.9µm. The mode-locked fiber laser generated the input pulses with amplification via a 20µm core PM Yb^{3+} doped fiber. Thus the pulse was not transform limited when it entered the pulse cleaner. A shorter pulse would permit the use of a shorter length of fiber and as would a smaller mode field diameter fiber. It was possible to run our mode-locked fiber laser in a regime where there was significant CW breakthrough by detuning the waveplates significantly from the optimum. This allowed us to directly observe the cleaning effect of the device by looking at the signal transmitted through the fiber before and after the analyzer. This data is shown at the bottom right of figure 3 and shows at least a 20dB suppression of the CW breakthrough. There is also some modulation of the oscillator spectrum. This is likely due to the relatively long length of fiber employed for this effort. Systems optimized for higher energy shorter pulses would use a shorter fiber length and have a wider transmission bandwidth.

Dispersion Control

Any laser system relying on chirped pulse amplification (CPA) requires careful management of the overall system dispersion. The front end for a large glass laser needs to stretch the laser pulse to 1-3ns in order to avoid damage from high peak powers in the main laser. Given that the Nd:Glass lasers use phosphate glass compositions with bandwidths of only about 2.2nm, this leads to a dispersion that is quite high (~500ps/nm). On a positive note, the narrow bandwidth limits the degree to which it is necessary to carefully balance the 3rd and 4th order dispersions. One advantage of an all fiber front end is that we can use a chirped fiber Bragg grating (CFBG) as the stretcher. This permits us to achieve the large required stretches in a compact format with minimal adjustments. Sample CFBGs have been obtained from the University of Southampton. Their measured group delay dispersion (GDD) and third order dispersions (TOD) relative to the requested specification is shown in table 1 below.

	50% grating	70% grating	Specification	Units
GDD	–106.04	–107.14	–105.50	ps^2/rad
TOD	1.40	0.92	0.81	ps^3/rad^2

Table 1: Measured CFBG GDD and TOD for two CFBGs with differing reflectivity vs. the specification.

The TOD of these gratings is quite small relative the GDD and thus the error bar in the measurement of the TOD is large. These gratings are also first generation test gratings and have only about 1/3rd the dispersion of the planned final gratings.

While the CFBG will supply the majority of the dispersion for the CPA system it is not easily adjustable. For large Nd:glass laser systems such as those that would operate on NIF or Omega, the compressor will not be easily accessible or adjustable. Thus some means of tweaking the overall system dispersion will be needed in the front end to compensate for the material in the system, imperfect mismatches between the stretcher and compressor and to detune the pulse from transform limit to accommodate experiments needing pulse widths up to 10ps. To do this our front end will include a pulse tweaker, which will consist of a pair of double passed parallel gratings with a fiber optic input and output. Angle of incidence and separation of the gratings will be adjustable in order to accommodate adjustments to the dispersion of the system. The roof mirror that provides for double passing the gratings will also be on a mobile translation stage to permit fine-tuning of the pulse timing. Ideally this tweaker will be placed after any signal splitting to accommodate independent adjustments of the dispersion and timing on each beamline.

Transport Fiber

A key requirement for this CPA system is the ability to remotely locate the front end up to 100m from the main amplifier chain. Combined with the necessity to launch 10nJ into the amplifier chain in order to maintain acceptable pre-pulse contrast the transport fiber must be well understood. We determined that standard single mode fiber would not transport the required energy over the required distance without unacceptably high self phase modulation occurring in the transport fiber. For a CPA system such as the one we would like to construct a change in phase due to intensity from the leading edge of the pulse to the center of the pulse of up to 2 radians can be accommodated [8]. Thus we wish to keep the self phase modulation in the transport fiber well less than 1 radian. To do this we had Nufern custom make single mode fibers with low numerical aperture and large mode field diameters (MFD). Two fibers were purchased, one with a 12.9µm MFD and one with a 16µm MFD. Figure 4 below shows theoretical and experimental data from these fibers.

Table summarizing non-linear limits of transport fiber

Input pulse width (ns)	Fiber MFD (µm)	Fiber attenuation (dB)	Input Raman scattering threshold energy (nJ)	Energy for B=1 at 100 m (nJ)	Energy for B=10 at 100 m (nJ)	Minimum bend diameter of fiber (mm)
1.2	12.9	0.24	258	16.6	166	100
3	12.9	0.24	645	41.4	414	100
1.2	16	0.2	395	28.2	282	75
3	16	0.2	988	70.5	705	75

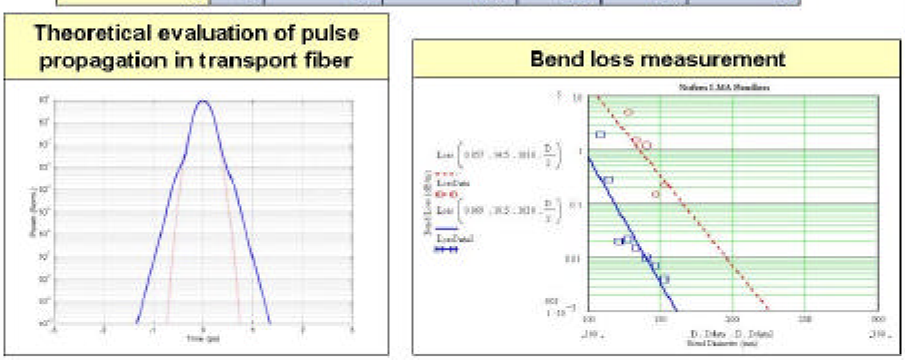

Figure 4: Top: table critical transport fiber parameters for 12.9µm and 16µm MFDs and 1.2 and 3ns pulse lengths, bottom left: theoretical evaluation of 1.2ns, 10nJ chirped pulse traversing 100m of 12.9µm MFD fiber blue line is recompressed pulse with SPM effects and red line is theoretical pulse recompression with no SPM effects, bottom right: measured bend loss sensitivity for the two fibers.

The table at the top of figure 4 shows calculated non-linear thresholds for the two fibers for the case of a 1.2ns stretched pulse and a 3ns stretched pulse. As expected the limiting factor is self phase modulation (energy at which B=1, B is the number of radians of accumulated phase between the center of the pulse and the leading edge due to SPM). In all cases, 10nJ can be propagated over 100m of fiber with acceptable non-linear phase accumulation. With low NA fibers bend loss is a concern. The two fibers were measured for bend loss sensitivity by taking a 5m sample and measuring transmitted power as a function of coil diameter. Data from this experiment is shown in the bottom right portion of figure 4. Bend diameters of 10cm in the 16µm mode field diameter case and 7.5cm in the 12.9µm MFD case were found to be acceptable. Some, but not excessive care would need to be taken in cable deployment for the system.

Amplifiers

There are three amplifiers in our proposed system. The first is a compressed pulse amplifier to bring the pulse energy into the 50-100nJ range, the second is an intermediate amplifier to bring the pulse to 1μJ and the last is a high energy amplifier to bring the pulse into the >100μJ range. We have previously reported on our large flattened mode (LFM) fiber, which we believe is a good candidate for the 100μJ high-energy amplifier [9]. At current state of the art with large mode area fibers commercially available, construction of a 1μJ amplifier is not particularly difficult, particularly at repetition rates of 10-100kHz, where average power is limited to 10-100mW. However, the compressed pulse amplifier is interesting not for its energy output so much as for the ability to achieve good pulse quality after amplification with essentially no stretching. Figure 5 below shows experimental data from a dechirped pulse train that was amplified directly from the output of the oscillator with no additional stretching. The fiber employed was a Nufern PLMA-YDF-20/400, 5m of this fiber was pumped with a 25W LIMO 976nm diode array capable of being focused to a 400μm diameter, 0.22NA spot. A 10nm bandpass filter was employed between the oscillator and the amplifier to reduce the bandwidth. Pulses were recompressed with a double passed pair of parallel gratings (1200g/mm) that were separated by 20mm at an angle of incidence of 58 degrees. Significant self phase modulation is seen to broaden the amplified spectra at the 50nJ level. Some additional pre-stretching may be necessary to avoid this effect in the final system. However good quality recompressed pulses were obtained.

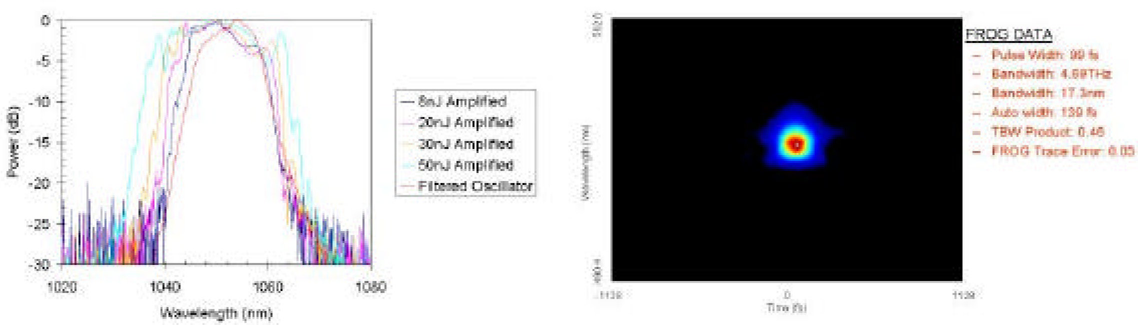

Figure 5: Experimental data from compressed pulse amplifier, left hand side: spectra as a function of output energy from the amplifier, right hand side: FROG data from 50nJ pulse train.

Preliminary System Tests

We have made a preliminary test of a portion of the full system at low energy (~10nJ) in order to validate the dispersion requirements of the system could be met. That is that pulses with good quality could be transmitted through the entire system and recompressed. The final compressor was designed to match the CFBG dispersion as closely as possible. The grating used was a 30cm gold grating fabricated at LLNL with 1485g/mm. The angle of incidence of the light was 47.5 degrees and a first roof mirror was place approximately 190cm from the grating in order to use the same grating for the "parallel pair". A second roof mirror permitted the grating "pair" to be double passed. A schematic of the partial system is shown in figure 6 below as well as FROG data from the recompressed pulses. Transmitted bandwidth through the system was about 5nm due to some gain tilt reshaping the spectrum. The compressed pulse was close to transform limited with a pulse width of 364fs and a time bandwidth product of 0.59. The system consisted of the components described above. A fiber mode-locked oscillator, followed by a pulse tweaker, a band pass filter, a compressed pulse amplifier, the CFBG, and two fiber amplifiers. The pulse selectors were run in a CW mode and the amplifiers were not turned up to high power so overall pulse energy through the system was in the 10nJ range. Experiments are in progress to reduce the repetition rate and increase the pulse energy into the 100μJ range.

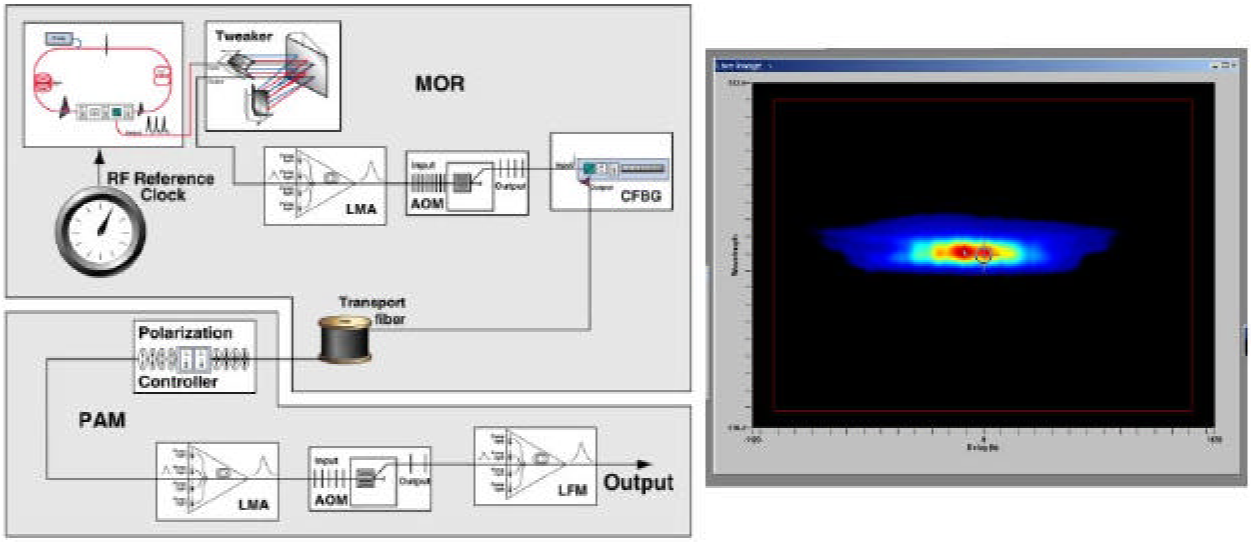

Figure 6: Preliminary system test: left hand side: schematic of the preliminary system, right hand side: raw FROG data from recompressed pulses. Recompressed pulses had 5nm bandwidth, 364fs pulse width and a time bandwidth product of 0.59.

CONCLUSIONS

We have presented a proposed all fiber front end for short pulse, high energy Nd:glass lasers. There are many unique considerations for these systems that pose challenges beyond what one would normally consider in designing a short pulse fiber laser system. We have also discussed a number of the components in detail and presented preliminary system results.

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