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ALL FIBER TECHNOLOGY FOR HIGH-ENERGY PETAWATT FRONT END LASER SYSTEMS

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We are developing an all fiber front end for the next generation high-energy petawatt (HEPW) laser at Lawrence Livermore National Laboratory (LLNL). The ultimate goal of the LLNL HEPW effort is to generate 5-kJ pulses capable of compression to 5ps at 1053nm, enabling advanced x-ray backlighters and possible demonstration of fast ignition. We discuss the front-end of the laser design from the fiber master oscillator, which generates the mode-locked 20nm bandwidth initial pulses through the 10mJ output of the large flattened mode (LFM) fiber amplifier.

Development of an all fiber front end requires technological breakthroughs in the key areas of the master oscillator and fiber amplification. Chirped pulse amplification in optical fibers has been demonstrated to 1mJ. Further increase is limited by the onset of stimulated Raman scattering (SRS). We have recently demonstrated a new flattened mode fiber technology, which reduces peak power for a given energy and thus the onset of SRS. Controlled experiments with 1st generation fibers yielded 0.5mJ of energy while significantly increasing the point at which non-linear optical effects degrade the amplified pulse. In this paper we will discuss our efforts to extend this work to greater than 20mJ using our large flattened mode fiber amplifier.

We are developing an all-fiber front end for a next-generation, high-energy petawatt (HEPW) laser at Lawrence Livermore National Laboratory (LLNL). We are seeking to make the front end of the laser similar to the successfully deployed NIF front end laser architecture, which includes a fiber laser master oscillator, fiber amplifier chain and fiber transport to the NIF amplifier bay. Optical fiber technology offers many benefits for front ends for high-energy short pulse laser systems. These benefits include packaging for turn-key, robust, environmentally stable and low maintenance operation. Furthermore, some technology, such as chirped fiber Bragg gratings offer unique features not available in their bulk optic counterparts. We have created a “straw-man” system schematic for our front end and it is shown in figure 1.

The planned front-end consists of an all-fiber mode-locked master oscillator, an electro-optic modulator (EOM) for pulse selection and amplified spontaneous emission control, a chirped fiber Bragg grating for pulse stretching (CFBG), a fiber pre-amplifier, a pulse width fail safe, transport fiber to take the pulses to the main amplifier bay and a final high energy fiber amplifier.

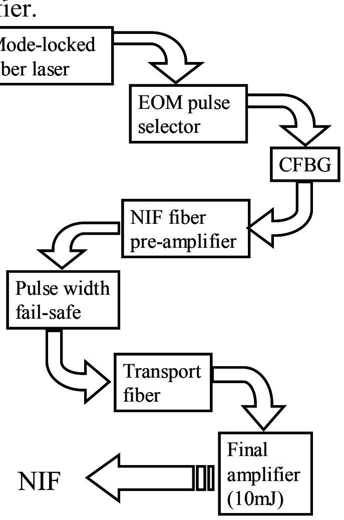

Fig. 1 Schematic of the proposed all-fiber front-end.

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Mode-locked fiber lasers have been demonstrated in the literature[1, 2, 3] with exceptional timing and energy stability as well as extremely broad bandwidths. We are in the process of studying these configurations to see which is best suited for our system needs or if there are improvements required for our system.

The CFBG is a chirped grating written into the core of an optical fiber such that the group delay as a function of wavelength is very controllable for pulse stretching up to a few nano-seconds. This technology is potentially very useful in short pulse laser front ends as one nominally has independent control over the group delay dispersion (GDD) and third order dispersion (TOD). Thus one can potentially compensate system dispersion issues up to second order that a matched stretcher-compressor might miss. This will be especially important for our system architecture in which we need to traverse greater than 80m of silica material to get from the master oscillator to the main amplifier chain. However, there is only one study in the literature[4] that we are aware of that looks at issues relating to using CFBGs in a short pulse system and those results were not promising. Should the CFBG fail to work out, another scheme for compensating the material dispersion of the fiber will need to be developed in order to realize a remotely located front-end.

Our design envisions flexibility surrounding the pulse energy and pulse width delivered to the target chamber. However, high energies and short pulse widths are not always independently adjustable parameters, as they can result in peak powers on the final system optics, which would damage or destroy such optics. Thus our design includes a pulse width fail-safe as a means of adjusting the final compressed pulse width. This will be done by using a pair of 1XN fiber optic switches to permit routing of the launched pulse through a selection of fiber lengths. The N individual fiber lengths will be selected to alter the pulse dispersion. In the case of the shortest length, the pulse will be fully compressed by the final compressor to its shortest pulse width. The remaining longer lengths of fiber will provide increasingly greater additional GDD and TOD to the pulse, mismatching it from the final compressor and resulting in a recompressed pulse which is longer than possible given the pulse bandwidth and for which the ringing due to the additional TOD is on the trailing edge of the pulse, which is optimal of most mission needs.

Presently NIF uses polarizing optical fiber for transport of long pulses from the master oscillator room (MOR) to the main amplifier bay. This fiber is essentially a polarization maintaining fiber with a depressed well index guiding structure[5]. The depressed well index structure results in the fiber mode increasing rapidly in diameter with increasing wavelength beyond a certain wavelength (commonly denoted the fundamental mode cutoff wavelength) determined by the details of the refractive index profile of the structure. This results in a high loss for wavelengths beyond this fundamental mode cutoff wavelength. By employing this structure in polarization maintaining fiber, it is possible to cause one polarization state (the fast axis guided mode) to be "cutoff" at a shorter wavelength than the other polarization state (the slow axis guided mode). This results in the creation of an operating window of typically 100nm in which only one polarization state is guided. However application of this fiber to short pulses has a fundamental weakness. The dispersion of the fiber is strongly varying in the region of interest and includes large TOD components that are strong functions of the precise fiber that will be used and the geometry it will be placed in. This is illustrated in figure 2 below, which shows the calculated GDD and TOD per meter for polarizing optical fiber as the operating window is moved over a range consistent with the expected variability due to manufacture of the fiber and the additional variability due to deployment conditions of the fiber. The fundamental mode cutoff wavelength can be shifted by 10s of nanometers via bending of the fiber.

To combat this level of variability in the dispersion we have proposed using a large mode area single mode optical fiber with active polarization control. This will permit a predictable dispersion that is constant with time due to the transport fiber, without introducing path delay created FM-AM conversion as has previously been seen with polarization maintaining optical fiber. A large mode area fiber will also permit maximization of the launched energy without the creation of B-integral issues. A large mode area fiber has been designed and ordered and will be tested in the next year.

It has been shown through internal modeling[6] that gain narrowing in the Nd:Glass amplifier chains will be the limiting factor in final pulse width delivered to the target. Furthermore high gain regenerative amplifiers that are the first amplification seen by the pulse after delivery from the MOR to the main amplifier bay

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typically induce most of this narrowing. A high gain, broad-band fiber amplifier, would greatly improve the performance of the overall HEPW system. However, to really make this effective one would like to use an Yb^{3+} fiber amplifier to launch up to 10mJ into the NIF amplifier chain. This is an order of magnitude higher in pulse energy than previously reported from a short pulse optical fiber amplifier[7]. We have recently developed a new waveguide design called a large flattened mode (LFM)[8].

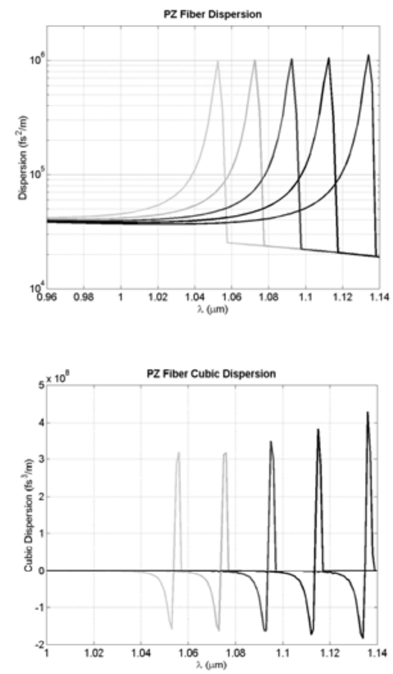

Fig. 2. Top: GDD per meter of polarizing optical fiber, Bottom: TOD per meter of polarizing optical fiber. Curves generated for slow-axis fundamental mode cutoffs between 1060nm and 1140nm at 20nm increments.

To date, the primary approach in scaling the pulse energy extractable from a rare earth doped optical fiber amplifier has been to scale the core size. So called large mode area (LMA) optical fibers permit increases in the extractable energy from the fiber core will decreasing the peak power in the core thus offsetting the impact of non-linear effects on the pulses which degrades the performance. The core size of a single mode optical fiber can be scaled to about 20µm diameter before one can no longer keep the fiber strictly single transverse mode. The core can be scaled as large as 50µm and schemes such as selective mode launch and bend induced attenuation of higher order modes can be employed to maintain good output beam quality. However, scaling beyond 50µm core size is problematic due to beam quality issues. At this core size, 1.2mJ has been extracted from an Yb^{3+} doped optical fiber amplifier, prior to the onset of limiting non-linear effects. Our LFM fiber design seeks to increase the output energy further by creating a fundamental guided mode, which is flat-toped rather than following the J_0 Bessel function shape found in a standard step index fiber design. This flat top shape is created by inclusion of a raised index ring surrounding the central core[9] (see fig. 3)

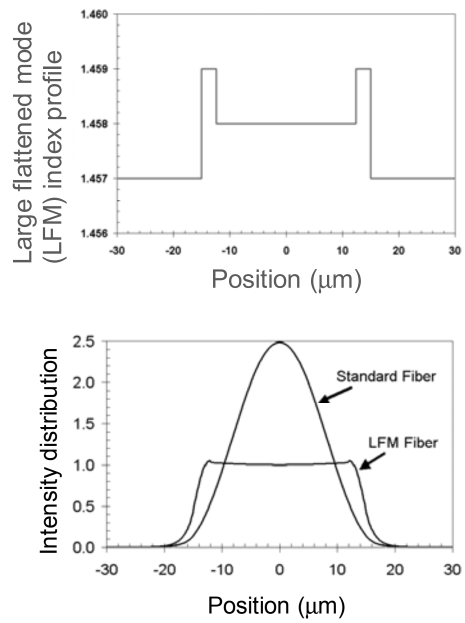

Fig. 3. Top: Refractive index profile for a large flattened mode optical fiber with a 50mm core diameter, Bottom: comparison of the intensity distribution of the fundamental mode of the fiber for the LFM fiber above and a standard fiber with the same core size. The modes have been normalized to carry the same equivalent energy.

In order to validate that this fiber would work as proposed, we purchased a 30-µm core, 0.06-NA, step-index, control fiber (Nufern) with a 400µm hexagonal cladding with a low index polymer coating (pump clad NA=0.37). The core was doped with Yb^{3+} such that there was an effective core absorption of 120dB/m at 977nm. We also purchased a nearly identical fiber from Nufern, but with the raised ring that gives the LFM fiber its distinctive index profile. The inner core diameter of the LFM was 25.3µm and the outer core diameter was about 30-µm FWHM, the effective NA of the structure was

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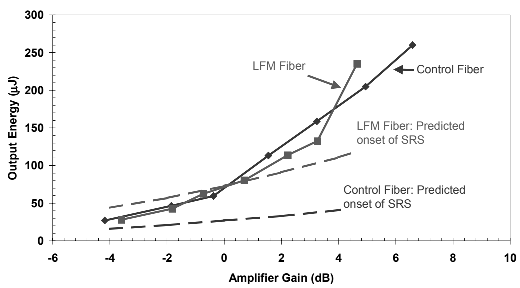
approximately 0.06. The outer cladding and Yb^{3+} doping were the same as for the control fiber.

We then coupled 1.2-ns, 1075-nm, 10-Hz stretched mode-locked laser pulses into 9.1m of the control fiber and 8.3m of the LFM fiber. The input energy coupled into the fiber cores was 15μJ. 977nm pump light from a 10W diode laser array was counter propagated through the fiber to pump the Yb^{3+} ions. The diode light was pulsed at 10Hz for 1ms timed to precede the arrival of the signal light. In figure 4 below, we show the amplified output energy of the two fibers on the top measured with a Molectron energy meter. As expected they produce roughly the same output energy as a function of pump diode current.



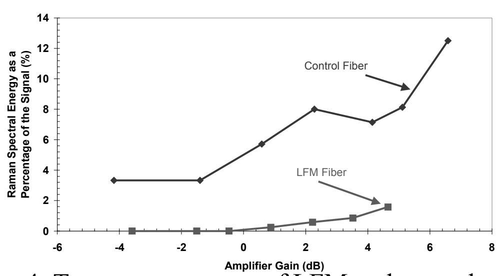


Fig. 4: Top: output energy of LFM and control fiber vs. amplifier gain along with predicted onset of SRS. Bottom: peak of Raman spectral band as a percentage of measured signal peak

In bottom picture however, we plot the percentage of the signal power contained in the first stokes spectra as measured with an Ocean Optics fiber coupled spectrometer. Here we see, the LFM fiber shows significantly less Raman energy build up as a function of diode current than the control fiber. This is in agreement with what we expected from the design. In addition, we achieved greater than 0.6mJ output pulses from the LFM amplifier with less than 5% of the energy in the Raman spectral band by utilizing pulses stretched to 3ns. With straightforward scaling of Yb^{3+} doping concentration to reduce the amplifier length, increasing the core size to 50μm and increasing the pump energy an optimized design could yield output pulses with greater than 10mJ of energy and virtually no degradation due to stimulated Raman scattering.

In summary, we are in the process of developing key fiber component technologies that will likely be needed in the future to deploy an HEPW system within the NIF architecture. This work is in progress, but we have identified the major issues and hope to have a front end system prototype running in the next 12 months that will permit a more complete understanding of all the potential effects.

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