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A 1-Joule laser for a 16-fiber injection system

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ABSTRACT

A 1-J laser was designed to launch light down 16, multi-mode fibers (400-µm-core dia.). A diffractive-optic splitter was designed in collaboration with Digital Optics Corporation[1] (DOC), and was delivered by DOC. Using this splitter, the energy injected into each fiber varied <1%. The spatial profile out of each fiber was such that there were no "hot spots," a flyer could successfully be launched and a PETN pellet could be initiated. Preliminary designs of the system were driven by system efficiency where a pristine TEM_{00} laser beam would be required. The laser is a master oscillator, power amplifier (MOPA) consisting of a 4-mm-dia. Nd:YLF rod in the stable, q-switched oscillator and a 9.5-mm-dia. Nd:YLF rod in the double-passed amplifier. Using a TEM_{00} oscillator beam resulted in excellent transmission efficiencies through the fibers at lower energies but proved to be quite unreliable at higher energies, causing premature fiber damage, flyer plate rupture, stimulated Raman scattering (SRS), and stimulated Brillouin scattering (SBS). Upon further investigation, it was found that both temporal and spatial beam formatting of the laser were required to successfully initiate the PETN. Results from the single-mode experiments, including fiber damage, SRS and SBS losses, will be presented. In addition, results showing the improvement that can be obtained by proper laser beam formatting will also be presented.

Keywords: Nd:YLF, fiber injection, multi-mode, fiber damage

INTRODUCTION

A 1-J laser (and subsequent 10-J laser) and beam distribution system was designed, built, and delivered for integration into the Pleiades experiment. The conceptual design for the laser and beam distribution system is shown in Fig. 1. The initiation of high explosives (HE) through the use of lasers has been shown to lower point-to-point detonation jitter. Assuming fibers of equal length, point-to-point-timing jitter can be reduced to < 10 ns if the fiber-to-fiber energy uniformity is better than ±5%.[2]

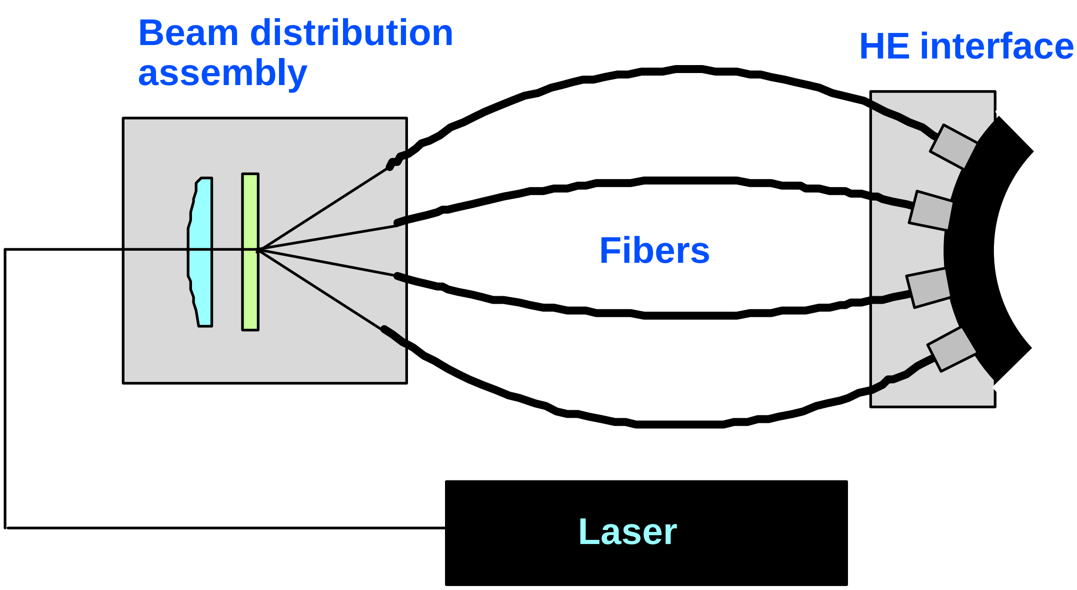

Figure 1. Schematic of an optical initiation system using a laser, fiber and beam distribution assembly.

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1. The 1-J laser (overview)

The total amount of laser energy required for the successful detonation of HE through fiber optics depends upon the total number of fibers. To allow the option of arbitrarily large numbers of fibers, a laser compatible with Nd:glass was chosen. These types of experiments are not limited by repetition rate but are often limited by available laser energy. Lasers using Nd:glass can achieve arbitrarily high energies (> 1kJ) .[3] To demonstrate the both the multi-point detonation and scalability principles, we designed and built a 1-J laser using Nd:YLF as the laser gain medium. The material, Nd:YLF, has excellent thermal properties that allow us to operate at repetition rates up to 20 Hz. It can operate at either 1047 nm or at 1053 nm, making it compatible with Nd:glass.

To achieve 1 J of laser energy, a master oscillator, power amplifier (MOPA) design was adopted (Fig. 2). A MOPA configuration using Nd:glass as the amplifier gain medium is capable of energies > 10 J. In addition, a MOPA geometry allows the operator to control the modal and temporal qualities of the beam in the relatively low-energy, oscillator. Since the amplifier medium is Nd:YLF (naturally birefringent), one must use a Faraday rotator-wave-plate combination, instead of a simple quarter wave-plate, to switch the beam into and out of the amplifier.

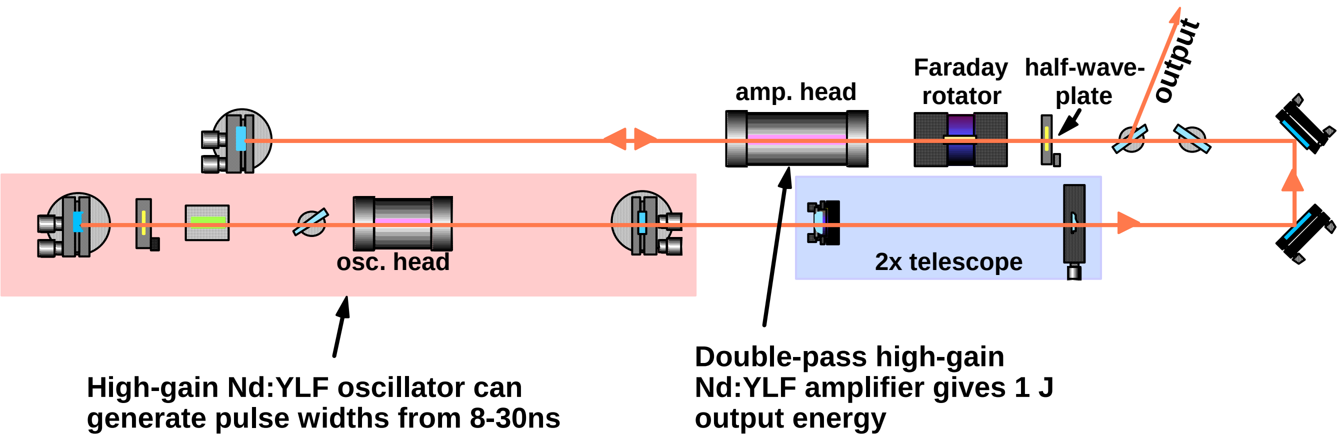

Figure 2. The MOPA configuration gives the user flexibility in both pulse width and laser energy.

2. Oscillator

2.1. Oscillator design and layout

The oscillator for the 1-J laser utilizes a standard, Continuum, two-lamp, 4-mm oscillator head and compatible power supply. A 4-mm dia., 65-mm long, Nd:YLF rod is the gain medium in a Fabry-Perot oscillator as shown in Fig. 3. The cavity length is ~50 cm. A quarter wave plate (QWP), a KD*P electro-optic Pockel's cell q-switch (Q-SW), and a thin film polarizer (TFP) control the q of the cavity. The QWP is oriented for highest cavity loss with the un-energized q-switch. The high-reflectivity mirror (HR) has a radius of curvature of 2 m and a reflectivity of > 99.8%. The output coupler mirror (OC) is flat and has reflectivity of 20%. The curved-flat Fabry-Perot oscillator configuration gives a very stable beam with a large mode diameter.

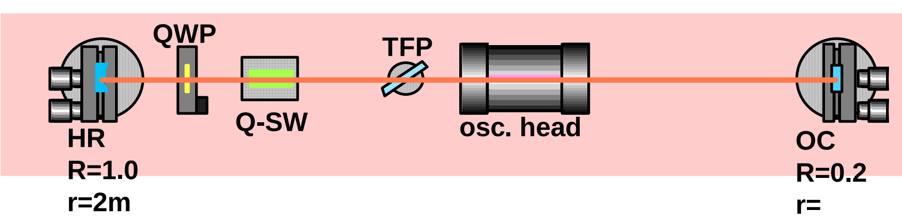

Figure 3. The 1-J laser uses a simple, q-switched, Fabry-Perot oscillator.

2.2. *Oscillator gain and pulse width control*

The single-pass, small signal gain of the oscillator head as a function of flashlamp voltage is shown in Fig. 4. This large variation in gain allows us to run the laser with pulse widths (τ) between 8 and 30 ns, simply by adjusting the flashlamp voltage. We have found that detonation threshold goes down with pulse width but damage threshold goes down with pulse width as well. We have not optimized these parameters but have had good success running the laser at ~12 ns. Using a 4-mm-dia. rod, the oscillator output energy is ~100 mJ.

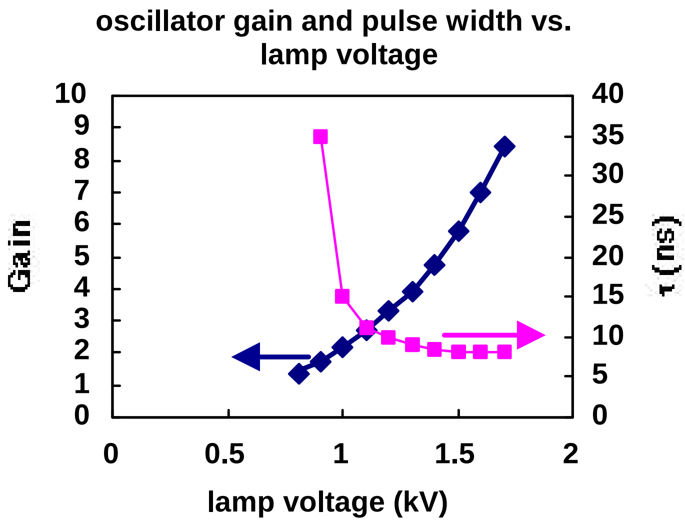

Figure 4. The large variation in the oscillator small-signal gain gives us the ability to run at a variety of pulse widths.

2.3. *Oscillator mode structure and its importance*

It is not only pulse width that is important, but pulse shape and mode structure as well. We have found that a highly multi-mode beam gives the smoothest temporal and spatial profile as well as the largest and densest mode spectrum.

A smooth transverse mode profile is important to eliminate hot spots that can damage optics or the fibers. A single transverse mode beam (TEM_{00}) gives a very smooth spatial profile but it does not have the dense longitudinal mode spectrum required for smooth coupling into the fibers and consistent detonation. As we see in Fig. 5, cavities with a single transverse mode have a mode separation of c/2L, and the cavity length limits the number of modes. A short cavity has a smaller fundamental mode size and can, therefore, support higher transverse mode beams with the same-sized mode-limiting aperture. Without a dedicated aperture, the actual Nd:YLF rod becomes the mode-limiting aperture. A highly multi-mode beam, with a high transverse mode number, has many modes which fit inside of the longitudinal mode spacing, giving a much denser mode spectrum. We have obtained our best results using a short (~50 cm) cavity where the rod is the mode-limiting aperture.

A dense mode spectrum has a number of advantages. First, the large number of modes increased the threshold for deleterious non-linear effects such as stimulated Raman scattering (SRS) and stimulated Brillouin scattering (SBS). A mildly multi-mode beam can see SRS effects in long fibers[4]. These SRS effects can shift the laser wavelength to higher order Stokes wavelengths that may overlap lossy bands of the fiber and reduce throughput efficiency (Fig. 6). With nearly single-mode beams, SBS dominates and the laser energy is actually reflected from the fiber back to the laser source[5-7]. Early in our experiments, the emphasis was more on bandwidth instead of mode density. Using an oscillator beam of ~M^2 = 3, we saw huge losses in transmission efficiency in 50-m long high-OH fibers. At 50% of the desired operating point, the transmission efficiency was down to 75% (Fig. 6). Due to time constraints, we were unable to systematically investigate the transmission efficiency of the high-OH fibers as a function of oscillator beam quality. Later experiments using a highly multi-mode oscillator (M^2 = 10) showed transmission losses of <5% in 25-m fibers. Our supply of 50-m fibers had been exhausted and we were unable to test them. It should also be mentioned that some significant amount of upconversion was observed during the ~M^2 = 3 transmission experiments in the high-OH fibers. The upconversion spectra are too broadband to be Anti-Stokes. At this point in time, we are unable to hypothesize the cause for this phenomenon.

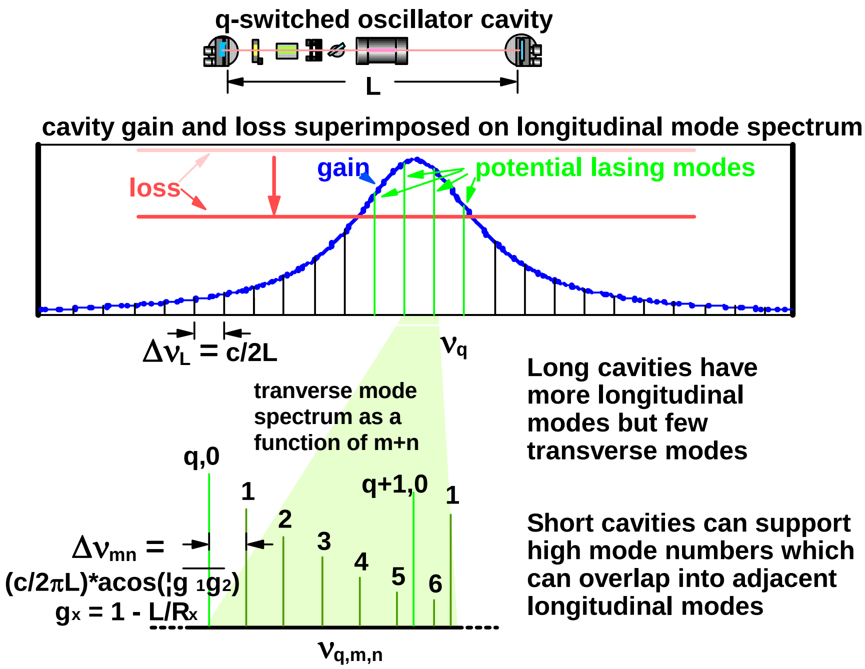

Figure 5. Highly multi-mode beams with high transverse mode numbers have much denser mode spectra.

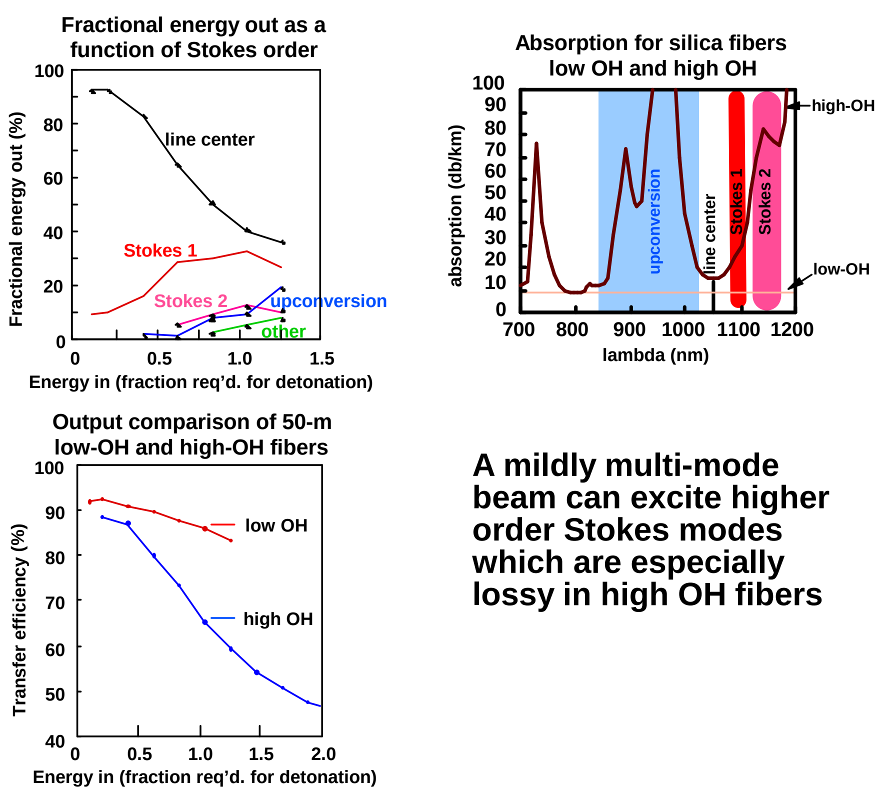

Figure 6. Mildly multi-mode beams can exhibit poor transfer efficiencies in long fibers due to SRS.

Second, a dense mode spectrum fills the fiber modes more uniformly and eliminates the hot spots, which are thought to be the causes of fiber damage and inconsistent or erratic detonation. We have found that consistently smooth fiber output profiles generated by very dense-mode-spectra lasers give the best detonation results (Fig. 7). Single- or mildly multi-mode beams often lead to fiber damage within the first 20 mm. The damage occurs at fluences as low as $15 J/cm^2$, far sooner than described in multi-mode damage results elsewhere. In addition, these low-order-mode beams often exceed the SBS threshold of the glass fiber. For example, a TEM_{00} beam with two dominant longitudinal modes can generate an SBS reflectivity of nearly 40% at input energies of 12.0 mJ as shown in Fig. 8. The damage thresholds and SBS reflectivities we observe are consistent with those reported elsewhere.[6,8] Notice the sharp turn-on of the SBS pulse and the depletion of the output pulse. The sharp turn-on is due to the length of the SBS medium causing pulse compression. Single-mode beams well above threshold in short SBS media do not exhibit this effect.[5] Based on the delay time of ~12ns, we estimate the onset of the SBS wave to be ~3m into the fiber. The longitudinal mode spacing is ~250MHz, well outside the ~100MHz SBS bandwidth of fused silica. Consequently, both modes can come over threshold independently while the overall SBS threshold is reduced by 2x.[9] A closer look at Fig. 8 shows the SBS feedback going all the way to the oscillator. The feedback manifests itself as a much longer tail on the input pulse. Without sufficient isolation, the oscillator energy then tends to fluctuate wildly, preventing any type of consistent operation.

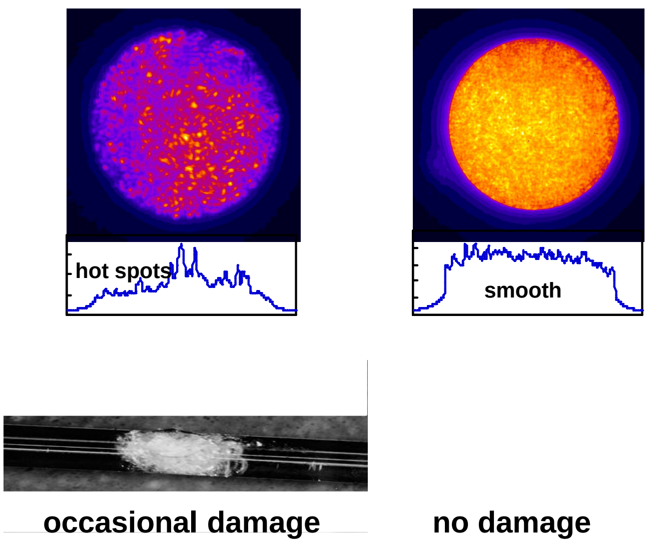

Figure 7. Highly multi-mode beams lead to smooth fiber profiles and no fiber damage.

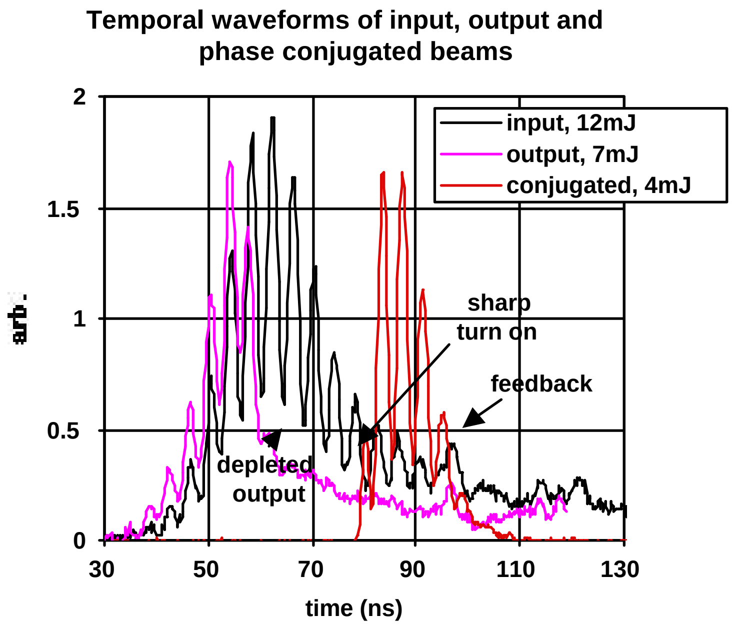

Figure 8. Waveforms showing the effect of SBS phase conjugation of a dual longitudinal mode TEMoo beam.

Third, the temporal profile of a highly multi-mode beam is generally quite smooth. The temporal profile of a single-mode beam is also smooth but single mode beams quickly exceed SBS and SRS thresholds. Mildly multi-mode beams often exhibit strong temporal modulation whose peaks can exceed the damage threshold of the glass fibers (Fig. 9).

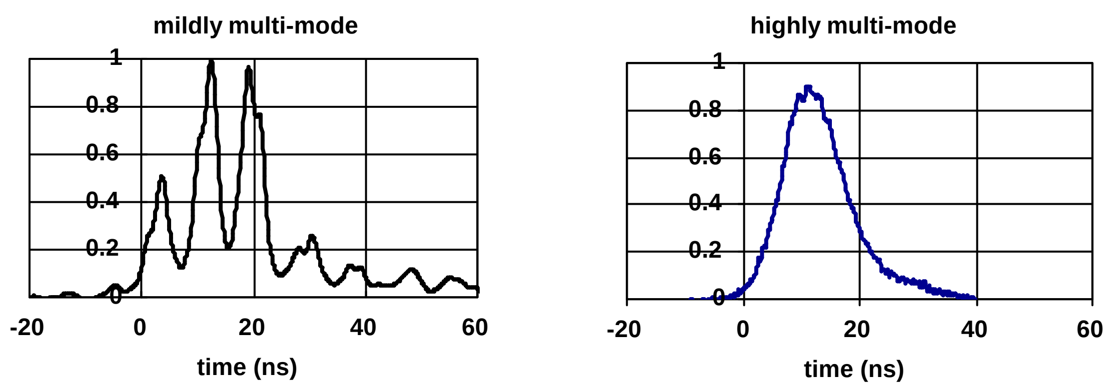

Figure 9. Temporal profiles for a mildly-multi mode and a highly multi-mode beam. Notice the strong temporal modulation in the mildly multi-mode beam.

A highly multi-mode beam does have a few disadvantages. First, the minimum focused spot diameter, d_{min}, that can be achieved is given by $d_{min} = 2\, f/^{\#} M^2 \lambda$, where M^2 is a measure of the quality of the beam (M^2 ~ times diffraction limited ~ the highest order transverse mode). For a reasonable optical system of f/16 and a wavelength of $\lambda \approx 1$ µm, $M^2 \leq 10$ to obtain a spot diameter of 320 µm for effective injection into 400-µm fibers. We have found that operating around $M^2 = 10$ gives us the best results.

The material, Nd:YLF, is naturally birefringent and can lase on two different lines. The higher gain line is at 1047 nm and the other line is at 1053 nm, compatible with Nd:glass. We have found that when the laser is operated as a stand-alone, 1-J laser, the 1047-nm line gives better results. Consequently, the oscillator must be configured to run at 1047 nm, as well as 1053 nm. For this reason, we have two types of oscillator rods. One type has 2°-parallel wedges cut parallel to the c-axis. The other type has 2°-parallel wedges cut perpendicular to the c-axis. In this manner we can change the wavelength of the oscillator simply by changing the rod, the wave plate and the TFP. The other oscillator optics are relatively insensitive to wavelength.

We have obtained the best results using a short, q-switched, (~50 cm) Fabry-Perot oscillator where the rod is the mode-limiting aperture. The beam quality is ~M^2 = 10 and the pulse width is ~12 ns.

3. One-Joule amplifier

3.1 Amplifier design and layout

The 1-J amplifier is shown schematically in Fig. 2. To obtain 1 J of output energy, the Nd:YLF amplifier must be used at the higher gain 1047-nm line. The output beam of the oscillator is expanded through 2x Keplerian telescope using standard plano-convex lenses. The p-polarized beam is turned using two turning mirrors and directed through two TFPs, a half-wave plate and a Faraday rotator. The half-wave plate and the Faraday rotator act as an optical switch. As the beam propagates to the left (toward the amplifier), the half-wave plate and the Faraday rotator rotate and un-rotate the beam polarization 45°, respectively, resulting in a net 0° polarization rotation. The beam propagates and gets amplified through the amplifier, hits the another mirror and returns through the amplifier for a second pass of amplification. After this 2nd amplification pass, the Faraday rotator and half-wave plate add for a net polarization of 90° and the beam exits off the TFP.

The amplifier is another standard, two-flashlamp, Continuum head using a 9.5-mm-dia. by 115-mm-long Nd:YLF rod. Since Nd:YLF is naturally birefringent, care must be taken to rotate the rod in the amplifier head such that the axis of interest is aligned with the polarization of the incoming beam. The wave plate is then adjusted to minimize the transmitted beam back toward the oscillator.

Alignment of the beam through the amplifier is not particularly critical but one should attempt to keep beam clipping to a minimum. Beam clipping leads to unwanted to diffraction and to energy loss.

3.2 Amplifier gain and operation point

The single pass gain of the amplifier head as a function of flashlamp voltage is shown in Fig. 10. Using an input beam of ~80 mJ (20% loss from mirrors, TFPs, wave plate, and Faraday rotator) into the amplifier at a single-pass gain of 11, a simple Frantz-Nodvik calculation predicts an output of ~1.3 J. In reality, we see only ~1.1 J. This difference is due to the fact that the leading edge of the beam overlaps itself inside the gain medium, diminishing the extractable energy. A corrected Frantz-Nodvik model, taking beam overlap into account, was written and predicts the correct output energy of 1.1 J.

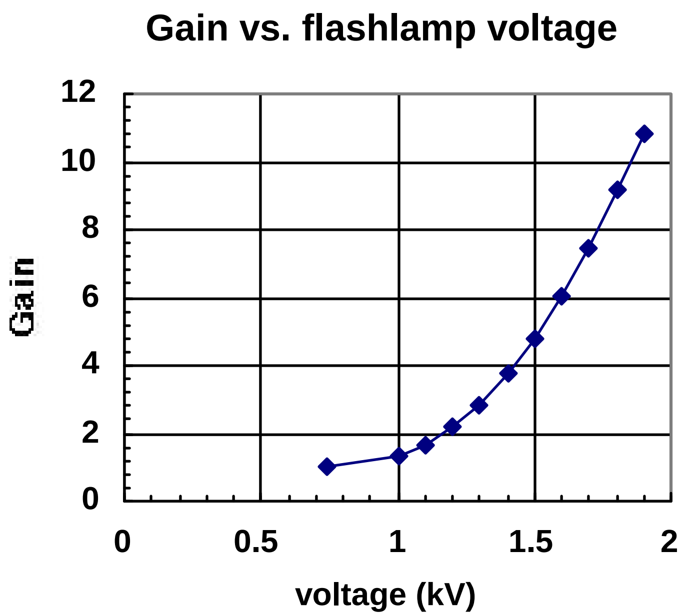

Figure 10. A single-pass amplifier gain of 11 can be achieved using a 9.5-mm-dia. Nd:YLF rod.

The timing of the amplifier pulse is set such that the gain reaches its peak when the oscillator pulse arrives. The peak gain is relatively broad (~2 µs) compared to the oscillator pulse (12 ns) and occurs ~170 µs after the start of the flashlamp pulse (Fig. 11).

This 9.5-mm-dia. Nd:YLF amplifier stores only 1.5 J of energy and, consequently, operates in a saturated regime. This saturation is actually advantageous since it fills in the beam and makes it more tophat shaped (Fig. 12). This tophat shape couples more readily and efficiently into the fiber, especially if the amplifier rod is imaged onto the fiber face. The tophat image shown in Fig. 12 is the actual profile at the fiber plane. The image is taken using Beamcode 6.2 and Cohu 4800 camera, with 23µm x 27µm pixels.

The 1-J amplifier can be run at 1047 nm or 1053 nm. Unlike the oscillator, it is not necessary to switch rods. The orientation can be adjusted by adjusting the half wave plate/Faraday rotator combination. The results presented thus far correspond to operation at 1047 nm. When operating at 1053 nm, we obtain ~600 mJ output due to the lower gain.

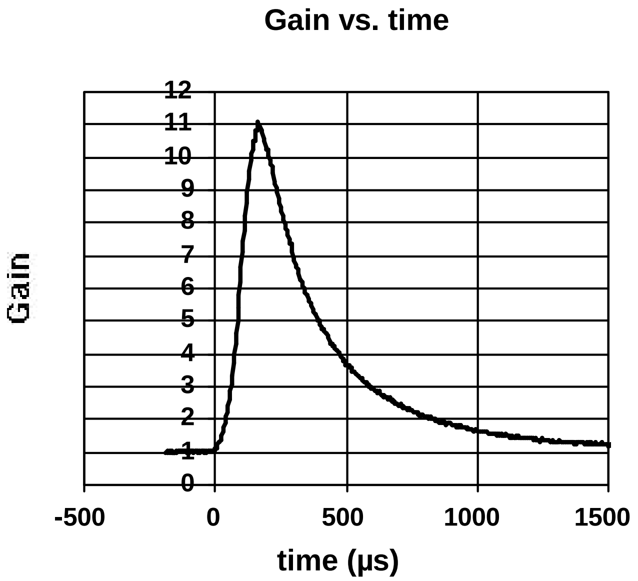

Figure 11. The peak of the 1-J amplifier gain occurs ~170 μs after the beginning of the flashlamp pulse.

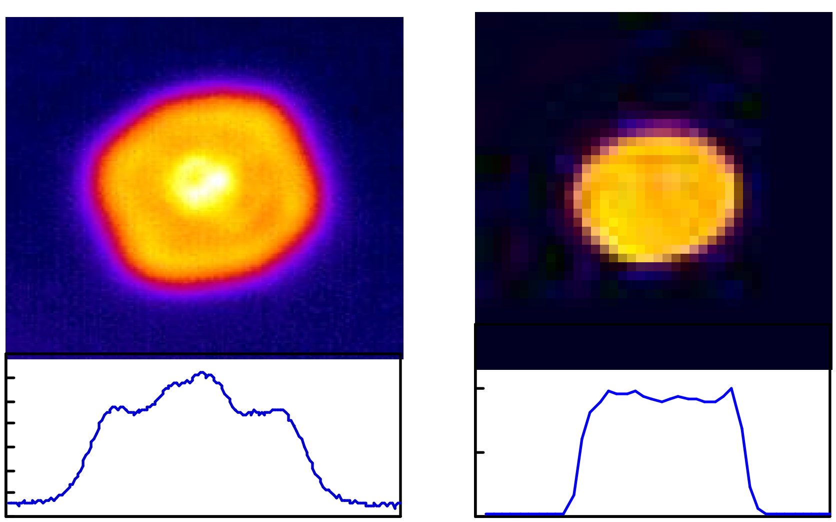

Figure 12. The gain saturation in the amplifier gives a more tophat beam profile.

4. Summary

To effectively launch significant quantities of energy down long fused silica fibers, one must design a laser such that the bandwidth and mode density are sufficiently large to prevent SRS and SBS losses. In addition, the mode density must be sufficiently large and the pulse shape must be sufficiently smooth to prevent fiber damage. However, the beam quality cannot be so poor that one cannot focus the light into the fiber. Successful operation cannot be based on energetics alone; it must be based on a systems approach to the entire problem. Adopting a MOPA scheme for the laser allows one the flexibility to perform the majority of the beam formatting at the oscillator while still offering the advantage of scalability to larger energy systems.

5. Acknowledgements

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