A Diode-Pumped Nd:YLF Master Oscillator for the OMEGA Laser

The OMEGA laser is a 60-beam laser-fusion system capable of producing a total of 30 kJ of ultraviolet (351-nm) energy on target,[1] where the temporal profile of the optical pulse applied to a laser-fusion target can be specified in advance. To accomplish this, the laser system consists of a master oscillator, a pulse-shaping system,[2] regenerative amplifiers (regens), large-aperture regenerative amplifiers (LARA), rod and disk amplifier chains, and frequency converters. A schematic of the laser chain is shown in Fig. 70.23. The pulse-shaping system (Fig. 70.24) is based on LLNL's conceptual design[3] and includes integrated-optics (IO) modulators driven by electrical waveform generators. The pulse-shaping system produces an optical pulse with a specific temporal pulse shape at the nanojoule energy level, which seeds the regens. The temporal profile of this low-energy seed pulse, when amplified and frequency tripled by the laser system, will compensate (1) for the temporal distortions caused by gain saturation in the regens and amplifiers and (2) for distortions caused by the tripling process and will produce the desired pulse shape on target. The overall gain of the OMEGA laser system from the pulse-shaping modulator to the target is approximately 10^{14}. This large gain puts extremely severe requirements on stability, reproducibility, and reliability of the pulse-shaping system and master oscillator performance. This article details the OMEGA requirements, describes the new diode-pumped master oscillator, and presents results from this newly fielded master oscillator.

OMEGA's Master Oscillator Design Requirements

The master oscillator for the OMEGA laser system must satisfy a number of requirements:

1. The wavelength of the oscillator must match that of OMEGA's Nd:phosphate glass amplifiers (1053 nm). This requirement automatically defines the choice of the laser medium for the master oscillator to Nd:YLF.

2. The oscillator must operate in a single-frequency regime. This requirement enables the stable and reproducible generation of complex optical pulse shapes and assures optimal frequency conversion.

3. The master oscillator must be *Q*-switched to produce enough energy to split among four or more pulse-shaping channels and to properly seed the various regens.

4. The duration of the master oscillator's *Q*-switched pulse must be >100 ns, and the timing jitter must be within ~10 ns to provide a constant pulse amplitude within the required 10-ns pulse-shaping window.

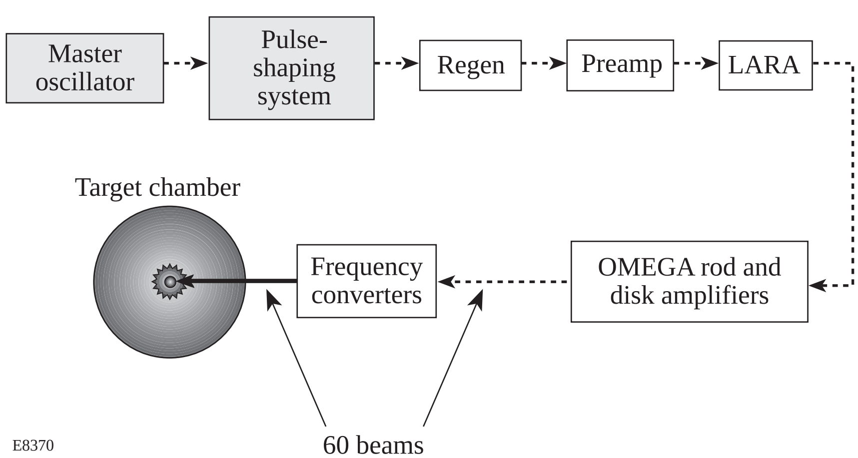

Figure 70.23
OMEGA laser system for ICF experiments.

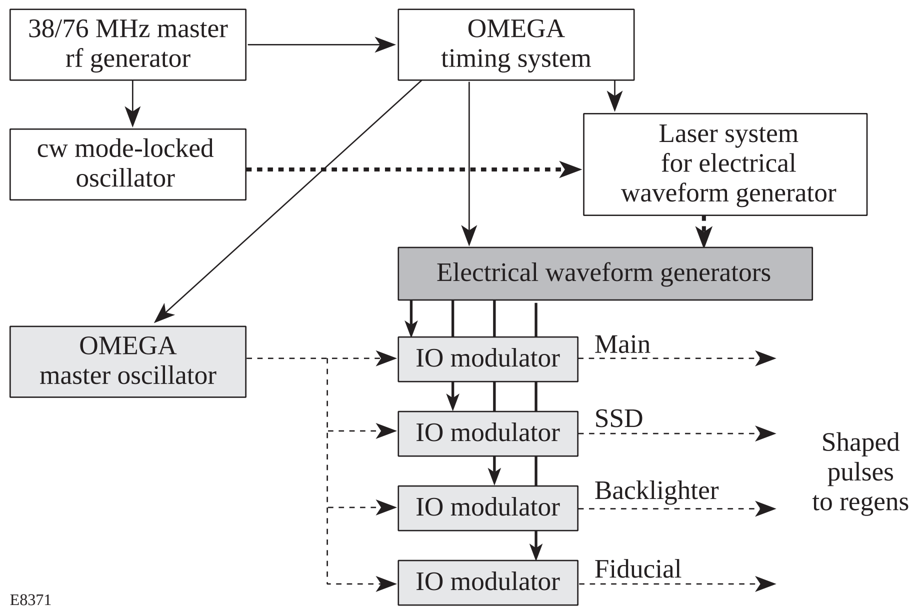

Figure 70.24
Block diagram of the pulse-shaping system for the OMEGA laser.

5. The master oscillator's *Q*-switched pulse must be externally synchronizable to the OMEGA timing system.

At present a flashlamp-pumped Nd:YLF laser is used on OMEGA. Although this laser satisfies all of the above conditions,[4] maintenance and reliability considerations have led us to develop a new diode-pumped version with significantly improved performance. The long-term maximum amplitude has been increased, and frequency stability has been dramatically improved, while the complexity, maintenance requirements, and footprint of this new laser have shrunk significantly.

Currently there are two major areas of interest in diode-pumped Nd:YLF laser development: high-power cw lasers and short-pulse *Q*-switched lasers. Even the most powerful cw lasers[5] cannot provide enough energy within a 10-ns pulse-shaping window to meet our requirement of >100 nJ in a 10-ns pulse in each of four channels. *Q*-switched, diode-pumped Nd:YLF lasers[6–9] are usually designed to generate short (3- to 10-ns) pulses with high peak powers. The short pulse width makes this type of laser unacceptable for satisfying the requirement for a constant pulse amplitude within a 10-ns pulse-shaping window. Passively *Q*-switched, diode-pumped lasers (for example see Refs. 10 and 11) cannot be precisely synchronized.

To ensure that the laser generates a single frequency, the laser should operate unidirectionally. The most commonly used technique to achieve this involves using an optical diode (Faraday rotator). This technique does require additional intracavity elements and consequently increases resonator losses, thus rendering it unsuitable for our use. Kane and Byer[12] have used nonplanar monolithic ring lasers; however, their use is restricted to laser materials with a large Verdet constant and no birefringence (Nd:YAG is such a material, but Nd:YLF is not). The most suitable way to provide unidirectional operation and *Q*-switching in a Nd:YLF laser is to employ an acousto-optic (A-O) *Q*-switch, which can be used for both birefringent[13] and nonbirefringent[14] materials.

The A-O *Q*-switched Nd:YLF laser meets most of the important requirements for the OMEGA master oscillator, namely the 1053-nm wavelength, single-frequency operation, high energy, and externally synchronizable requirements. However, close attention must be paid to the long (>100-ns) pulse width generation and high stability requirements.

There are no commercially available lasers with the specifications required for use on the OMEGA laser. In particular the wavelength (1053 nm) and long pulse duration (>100-ns) requirements are not commonly required in commercial systems.

Laser Design

The diode-pumped, single-frequency Nd:YLF laser (Fig. 70.25) is based on a triangular ring cavity with two spherical mirrors and a prism that doubles as an active element. The resonator is very similar to the Nd:YAG laser described in Ref. 15. In that design one of the resonator mirrors was deposited on the laser element; however, in our design we have moved the active element away from one of the mirrors to avoid spatial hole burning.[16] This residual hole-burning effect, when an active element is located at one of the ring cavity mirrors, cannot be fixed in our case by displacing the pumped volume from the cavity TEM_{00} mode as suggested in Ref. 17 because we use a fiber-coupled pumping diode and the pumped volume is larger than the TEM_{00}-mode volume. We use a fiber-coupled pumping diode so that the water-cooled laser diode can be removed from the laser head for enhanced laser stability. The diameter of the pumped volume for fiber-coupled diodes is relatively large (~0.4 mm) compared to other designs. This large volume reduces the efficiency of the laser but increases the overall stability of the diode-pumped laser. For our application the enhanced stability is more important than the efficiency of the master oscillator. The ring cavity has been chosen to provide traveling-wave unidirectional lasing and hence easier single-frequency operation. Both cavity mirrors are spherical with a 10-cm radius of curvature. The distance between the mirrors is approximately 30 mm. The angle of incidence for both mirrors is ~11°. The end mirror has maximum transmission for the pump radiation (797 nm) and maximum reflection for the 1053-nm laser wavelength. The output coupler has a 95% reflection coefficient at 1053 nm.

A 4 × 4-mm-cross-section, *a*-cut Nd:YLF element has Brewster-angled entrance and exit surfaces cut for 1053-nm operation (*c* axis is perpendicular to the resonator plane). Its on-axis thickness is 8 mm and has been calculated to compensate for the astigmatism from the two off-axis spherical cavity mirrors.[18] To provide maintenance-free operation no adjustable mounts were used for cavity alignment. The laser was assembled on a 50 × 30 × 30-mm Zerodur base plate to minimize thermal drift and improve long-term stability. A precisely machined metal template allows accurate placement of the carefully machined mirrors (flattened barrels) to eliminate the necessity for fine alignment of these mirrors. The active element is glued to a miniature piezo-translator (Physik Instrumente) for cavity-length adjustment, which is in turn mounted on a Zerodur standoff glued to the Zerodur base plate. The A-O modulator (QS080-2G-RU1, Gooch & Housego) assures a unidirectional prelase phase prior to *Q*-switching. The A-O *Q*-switch has plane-parallel surfaces (AR coated for 1053 nm) and can be aligned without disturbing the cavity alignment. Unidirectional operation is achieved by using the self-feedback mechanism in the A-O *Q*-switch, which is described in detail in Ref. 19.

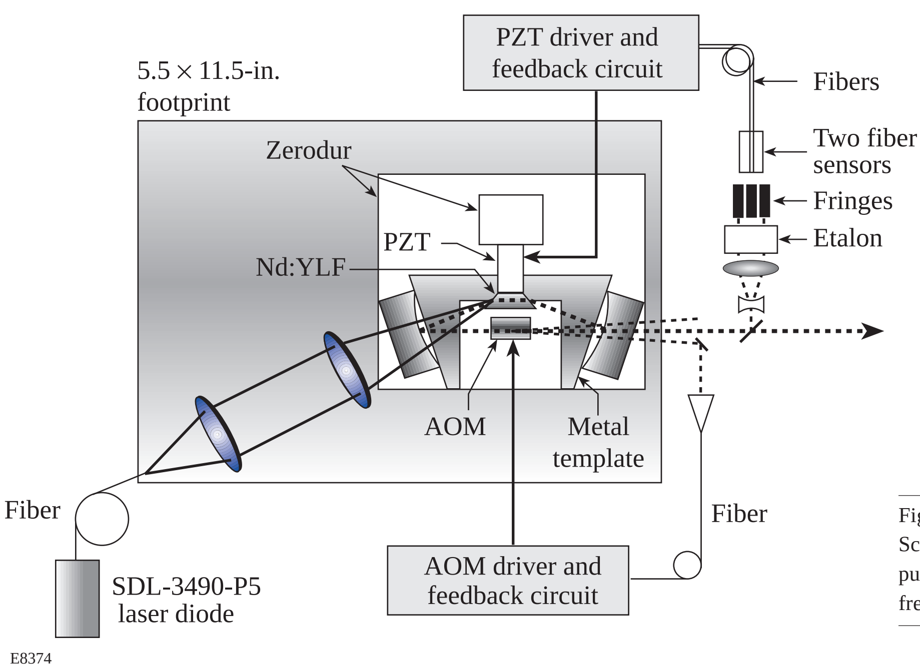

Figure 70.25
Schematic of the diode-pumped, single-frequency, pulsed OMEGA master oscillator with amplitude and frequency feedback systems.

The laser is pumped by 700-μs square pulses at a 5-Hz repetition rate generated by an SDL-3490-P5 fiber-coupled laser diode (nominal 5-W output). The OMEGA front-end laser system operates at 5-Hz repetition rate that reduces thermal problems in the master oscillator and extends the lifetime of the diode. The image of the output 0.4-mm-diam fiber surface is relayed into the active element of the laser by using two 25-mm-focal-length spherical lenses AR coated for 797 nm. Both lenses are aligned and assembled together with the fiber port. The position of the pumped volume can be aligned to the TEM_{00} cavity mode by adjusting the whole lens-fiber unit.

The low duty cycle of the oscillator obviates the need for a cooling system on the active element. The laser resonator is thermally uncoupled from the environment. The laser requires only two adjustments: alignment of the pumped volume in the active element and the A-O *Q*-switch position for unidirectional operation. The laser layout is shown in Fig. 70.26.

Experimental Results

We have found that a low rf power of ~5 mW_{rf} is sufficient for unidirectional operation. We have achieved a very high contrast for the counter-propagating beams (>1500:1). As mentioned above, unidirectional operation is essential to maintain the single-frequency regime. In this operating mode the prelase stage exhibits regular, slowly decaying relaxation oscillations [Fig. 70.27(a)], which cause significant amplitude and temporal jitter of the subsequent *Q*-switched pulse. To stabilize the prelase phase we have developed a negative amplitude feedback with a constant offset. The offset provides the required rf power level to achieve unidirectional operation during the prelase phase. One of the beams diffracted by the A-O modulator is coupled into the 0.4-mm multimode fiber

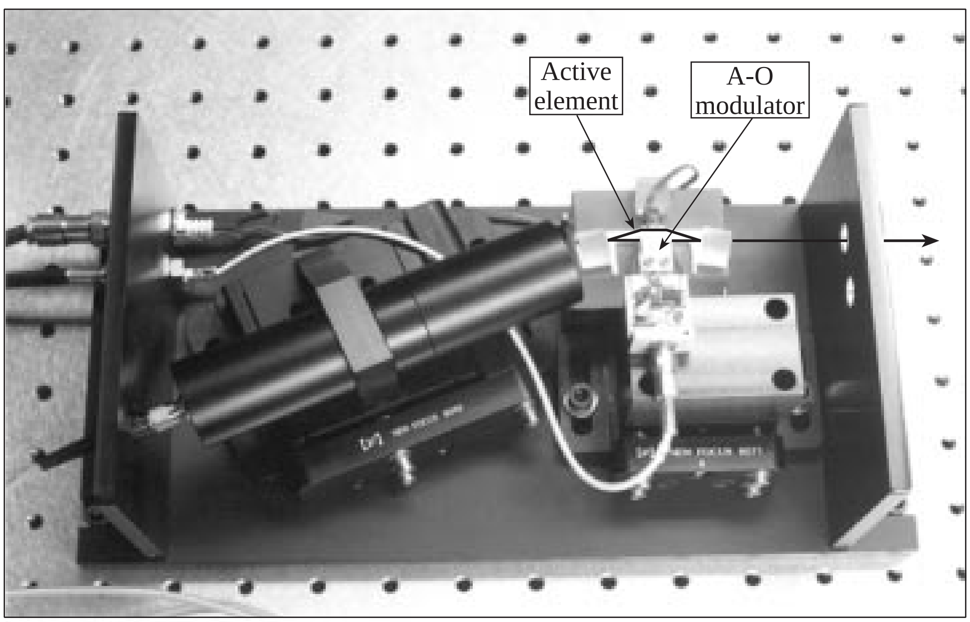

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Figure 70.26
The OMEGA master oscillator layout. It consists of three units: laser cavity (no adjustments required); A-O modulator (adjusted for unidirectional operation); and pump unit (adjusted for maximum laser output).

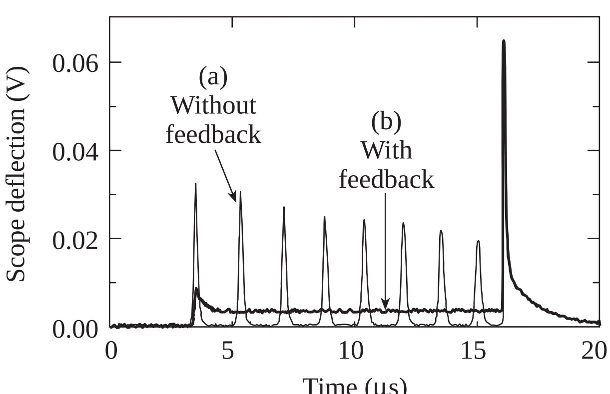

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Figure 70.27
Oscillograms of the prelase phase: (a) single-frequency operation, no amplitude feedback; (b) same with the feedback.

and sent to a diode that generates the feedback signal. Increased feedback increases the rf power to the A-O modulator, thus increasing the cavity losses and stabilizing the laser output. With amplitude feedback stabilization a very smooth prelase phase is observed [Fig. 70.27(b)], and the externally triggerable *Q*-switch leads to high amplitude stability and low temporal jitter of the output pulse.

At the lowest rf power required for unidirectional operation (~5 mW_{rf}) the laser generates a ~300-ns pulse of ~5-μJ energy. The pulse width is defined by the removable *Q*-switch loss. To maintain unidirectional operation and obtain high stability and low jitter, the laser must work close to threshold. For a given resonator configuration the energy content of the *Q*-switched pulse is closely related to the pulse width. The self-feedback mechanism of the A-O enforced unidirectional operation[19] is crucial for generating long single-frequency pulses because of the very low rf power required for the unidirectional prelase phase and hence low removable loss level. By increasing the offset in the amplitude feedback system and the pumping energy, we have been able to obtain stable single-frequency pulses with widths as short as 30 ns and energies of ~18 μJ. For use in the OMEGA laser chain the laser has been adjusted to generate an externally triggerable single-mode pulse of ~160-ns duration and ~10-μJ pulse energy. As a test of the laser stability and reproducibility, 100 laser pulses taken within 0.5 h with the laser operating at 5 Hz were recorded using a 1-GHz, 4-GS/s Hewlett-Packard 54720A digitizing oscilloscope. Figure 70.28(a) shows the average pulse shape (solid line) and its amplitude and temporal rms deviations (dashed lines). Figure 70.28(b) shows the same experimental data as Fig. 70.28(a), but the effect of the build-up jitter has been removed. By comparing Figs. 70.28(a) and 70.28(b) we conclude that the fluctuations seen in Fig. 70.28(a) are mostly due to the build-up time jitter (the long-term temporal jitter of the peak of the pulse is <7 ns rms). These data clearly show that the laser demonstrates excellent amplitude stability and pulse-shape reproducibility. The short-term (0.5-h) amplitude stability of the pulse has been measured to be ~0.3% rms. The long-term (8-h) stability is ~0.6% rms. The variation of the pulse width (which has an average FWHM of 159 ns) is ~0.7 ns rms. The achieved pulse duration and the remarkable stability of the pulse provide a constant pulse amplitude, with a variation of <1%, within the 10-ns pulse-shaping window. To maintain these excellent properties, the output beam must be handled very carefully. Even immeasurably small amounts of back reflections (from such sources as diagnostics, fibers, or fiber couplers) can reduce the stability significantly.

In all the experiments reported here, the laser was operated in the TEM_{00} mode despite the large pump volume. This mode of operation, which involves operating close to threshold with an extended prelase phase, helps the laser maintain a single longitudinal and spatial cavity mode.

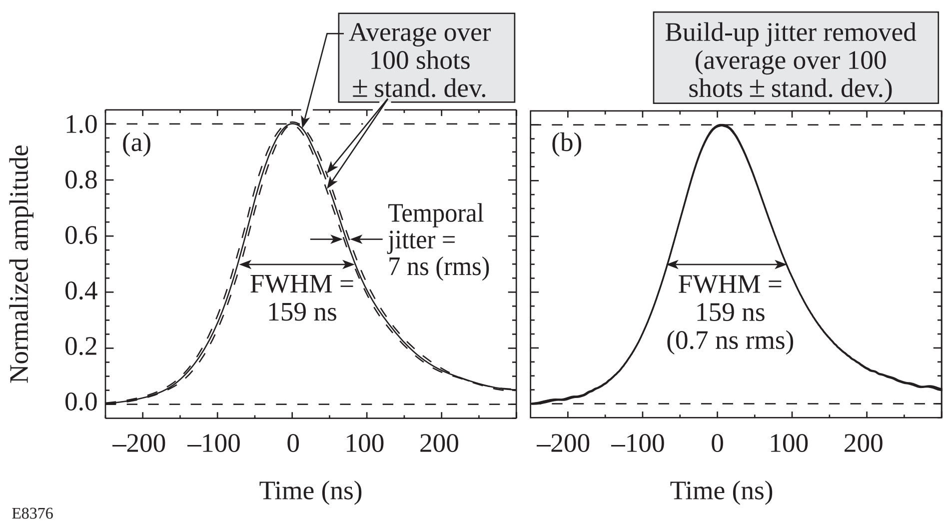

Figure 70.28
(a) The average pulse shape (solid line) and amplitude and temporal rms deviations (dashed lines) from the output *Q*-switched pulse for 100 shots taken within 0.5 h. (b) The data as in (a), but with the build-up jitter removed (all three lines, average and average ±rms fluctuations, virtually overlap). This indicates that all fluctuations in the left graph are mostly due to build-up time jitter of 7 ns rms, which is very small compared to the 159-ns pulse width (FWHM).

The optical efficiency in this *Q*-switched laser is ~5%. This relatively low optical efficiency is due to several factors: (1) the pump volume is large, exceeding the TEM_{00} cavity-mode volume; (2) the output coupler has not been optimized; and (3) the pump beam is slightly vignetted by the cavity mirror. However, for this application, optimal efficiency is not of major importance.

Long-term, single-frequency operation and stability are achieved by incorporating a frequency stabilization scheme. In this design 10% of the laser output is expanded and sent through a low-finesse, solid, temperature-controlled etalon to create fringes. Two fiber sensors straddle one of the fringes such that the difference between optical signals in the fibers is zero. Any fringe shift leads to a signed error signal that feeds into the (biased) PZT driver; this corrects the cavity length and drives the error signal to zero.

Conclusions

We have developed a diode-pumped, single-frequency, pulsed Nd:YLF master oscillator for the OMEGA laser system. Output pulses have been generated that have 30- to 300-ns duration and 5- to 18-μJ energy with high amplitude stability (<0.6% rms), low timing jitter (<7 ns rms), and long-term frequency stability of <100 MHz over periods of many hours without observable dual-mode operation. The laser adjusted for 160-ns pulse width and 10-μJ pulse energy satisfies all OMEGA requirements and is currently being incorporated into the OMEGA laser system.

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