All-Solid-State, Diode-Pumped, Multiharmonic Laser System for Timing Fiducial

Introduction

Laser timing fiducial signals are required as a timing reference for numerous laser and target diagnostics for inertial confinement fusion experiments. On OMEGA, infrared as well as visible and ultraviolet timing fiducial signals are needed to match the wavelength sensitivity of various diagnostics. Currently, a flash-lamp–pumped Nd:YLF/Nd:glass laser system operating at 1053 nm with frequency conversion to the second and fourth harmonics (527 and 264 nm) is used.[1] The system consists of a Nd:YLF master oscillator; a pulse-shaping system; a flash-lamp–pumped Nd:YLF regenerative amplifier; a Nd:glass, large-aperture ring amplifier; and frequency-conversion crystals. This fiducial laser system has a complicated design, a low repetition rate, low harmonic conversion efficiency, high maintenance because of flash-lamp pumping, and occupies a 5 × 14-ft optical table and a rack of electronics. We present an all-solid-state, diode-pumped, compact laser fiducial system that satisfies all OMEGA requirements, reduces the system complexity, and improves reliability while significantly reducing the space requirements.

Fiducial Laser System Requirements

The OMEGA fiducial laser system must produce a 3.5-ns comb of 200-ps FWHM optical pulses separated by 0.5 ns at IR, green, and UV wavelengths. A Nd:YLF laser system with second and fourth harmonic generators is used to produce IR, green, and UV fiducial signals. The amplitude variation of each pulse in the comb must not exceed 50% of the maximum. The required IR/green comb energy is 1 mJ. The most critical requirements for the fiducial system are 10-mJ energy at UV (4ω) fiducial and a stable time delay (~165 ns) between the IR/green and UV fiducials.

High-UV fiducial energy is required because of low photocathode sensitivity for the x-ray streak cameras employed as important OMEGA target diagnostics. A UV multimode fiber delivery system is used to couple fiducial combs into the diagnostics. The required UV energy is 10 μJ at the output of a fiber launcher. OMEGA needs up to 19 channels of UV fiducial; therefore, a 19-fiber bundle is used to launch the UV comb into the delivery fibers. To provide equal energy distribution and misalignment insensitivity for the fiber-bundle launcher, a UV fiducial beam must significantly overlap the 19-fiber bundle, bringing the total UV comb energy required to 10 mJ. Frequency-conversion efficiencies of 50%–75% for both second and fourth harmonic generation have been demonstrated;[2] therefore, the required IR energy should be in the 20- to 40-mJ range.

The relatively long delay between UV and IR/green fiducials is dictated by the physical location of various OMEGA diagnostics. IR/green fiducials must be generated ~165 ns before the UV comb to provide the simultaneous arrival of the fiducials to all OMEGA diagnostics. A 165-ns delay line is required between the IR/green and UV fiducial fiber launchers.

Laser System Description

A block diagram of the proposed system is shown in Fig. 103.33. The system is seeded by a shaped comb produced by a pulse-shaping system.[3] A single-frequency, diode-pumped Nd:YLF OMEGA master oscillator (OMO)[4] produces a 20-ns square pulse for shaping. The first integrated optics modulator is driven by the 24th harmonic of the 38-MHz OMEGA master-timing RF source. The second modulator is driven with a gate pulse that is precompensated for pulse-shape distortion caused by gain saturation in the amplifiers and gates an eight-pulse fiducial comb. A Nd:YLF OMEGA diode-pumped regenerative amplifier (ODR)[5] boosts the comb energy from tens of picojoules to ~4 mJ, the main portion of which is used as an IR fiducial and for generating a green fiducial.

An additional ODR is added to the system to provide the required 165-ns delay with a small footprint and without beam degradation. At the same time, it produces the additional gain required to achieve the UV energy specification. A portion of the ODR output is used to seed the second regenerative amplifier designated ODR+. A double-pass, diode-pumped amplifier provides additional gain and is discussed further in **Two-Pass,**

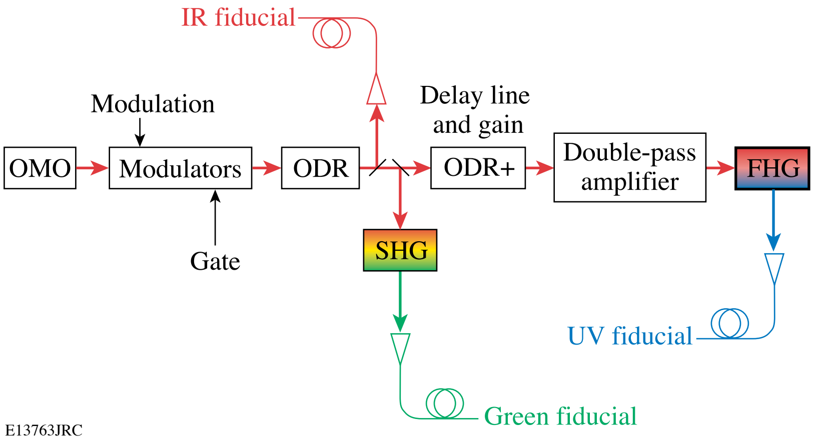

Figure 103.33
A block diagram of the proposed OMEGA fiducial laser system. OMO is the OMEGA master oscillator, ODR is the OMEGA diode-pumped regenerative amplifier, SHG and FHG are the second and fourth harmonic generators. The ODR, seeded by a pre-compensated fiducial comb, produces IR and green fiducial signals. ODR+ provides the necessary delay between IR/green and UV fiducials.

Diode-Pumped Nd:YLF Amplifier. Second-harmonic generation (SHG) and fourth-harmonic generation (FHG) are realized with BBO (beta-barium borate) crystals.

The ultraviolet pulses are launched into a bundle of 19 UV fibers to distribute UV fiducials to various OMEGA diagnostics.

Two-Pass, Diode-Pumped Nd:YLF Amplifier

The double-pass amplifier must produce 20 to 40 mJ of output energy in IR. Amplifier efficiency has to be estimated for the appropriate pump power choice. Amplifier efficiency includes (a) pump energy to active-element upper-state energy-conversion efficiency and (b) upper-state energy to amplifier output conversion efficiency.[6] Typical efficiencies for a Nd:YLF amplifier pumped by a fiber-coupled diode array through a dichroic mirror are

- Pump re-imaging optics transmission: 0.94
- Dichroic mirror transmission: 0.93
- Pump absorption: 0.8
- Quantum efficiency: 0.72

Pump energy to upper-state energy-conversion efficiency: 0.5.

Storage efficiency is calculated as follows:

$$\eta_s = \left[1 - \exp\left(-t_p/t_f\right)\right]\Big/\left(t_p/t_f\right),$$

where t_p is the pump-pulse width and t_f is the active medium fluorescence lifetime. In the case of diode pumping, when the pump-pulse shape and wavelength do not change with the pulse duration increase, it is beneficial to make the pump pulse longer to increase the total stored energy. For Nd:YLF with $t_f = 0.5$ ms, a 1-ms pump pulse is used.

- Storage efficiency: 0.43
- Beam overlap efficiency: 0.75
- ASE loss: 0.05
- Gain extraction efficiency: 0.95

Upper-state energy to amplifier output conversion efficiency: 0.29

Total diode-pumped, Nd:YLF amplifier optical-to-optical efficiency: <0.15

Achieving 40 mJ of amplifier output energy requires 270 mJ of pump energy or 270 W of quasi-continuous wave power from a fiber-coupled diode array. To produce a uniformly pumped volume, an active element is pumped from both sides by 150-W, fiber-coupled diode packages from Apollo Instruments (Irvine, CA). The delivery fiber has a 1-mm core diameter. To avoid optical damage of the active element, the fluence is kept below 5 J/cm^2, and the delivery fiber is re-imaged into an active element with 2× magnification. Using the Frantz–Nodvik equation,[7] the output energy of an amplifier was calculated (Fig. 103.34). Achieving a >40-mJ amplifier output requires >10-mJ input energy.

An ODR produces ~4 mJ of energy when pumped with two 25-W fiber-coupled diodes, which yields an amplifier output of only 25 mJ. In order to increase amplifier input energy, the ODR+ is pumped with one 150-W fiber-coupled diode array (Apollo Instruments). The ODR+ output energy is >13 mJ at the maximum pump energy (Fig. 103.35). With this input, the amplifier produces ~50 mJ of IR, meeting the energy requirement.

The double-pass, all-solid-state, diode-pumped Nd:YLF amplifier shown in Fig. 103.36(a) is built as a generic platform for use in a variety of applications, including a laser system for OMEGA frequency-conversion crystal tuning.[8] An input telescope can accommodate input beams with diameters in the range of 1 to 8 mm. The output telescope resizes and collimates the beam for efficient frequency conversion. A built-in fiber pickoff allows monitoring of the amplified pulse shape with a fast photodetector and oscilloscope. The amplifier output beam profile shown in Fig. 103.36(b) is excellent.

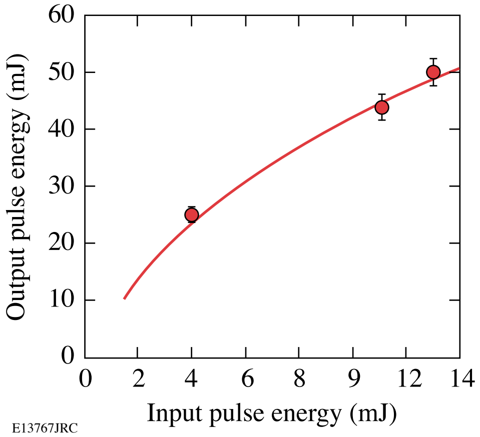

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Figure 103.34
The output energies of a double-pass Nd:YLF amplifier calculated using the Frantz–Nodvik equation (solid line) and measured (open circles) are in good agreement.

A block diagram of the frequency conversion setup is shown in Fig. 103.37. BBO crystals are utilized for frequency conversion to the fourth harmonic. An 11-mm-long type-I crystal is employed for SHG, followed by a 6-mm-long type-I crystal for FHG. A fused-silica Pellin–Broca prism is used to spatially separate the UV fiducial beam, and a telescope matches the beam size to efficiently launch the UV pulses into a multimode fiber bundle.

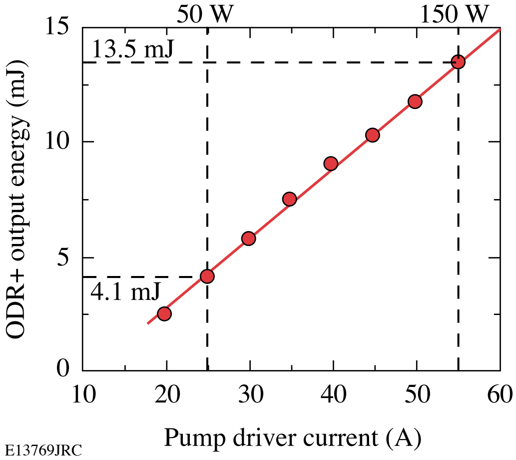

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Figure 103.35
ODR+ is able to produce sufficient energy for efficient double-pass amplifier energy extraction.

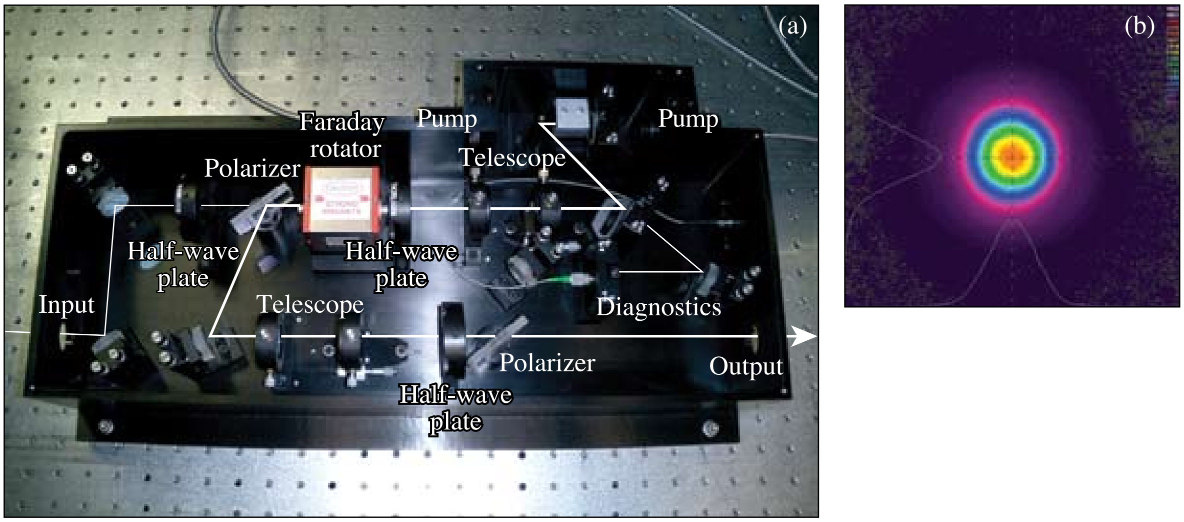

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Figure 103.36
(a) All-solid-state, diode-pumped, double-pass Nd:YLF amplifier. (b) The output beam profile is excellent.

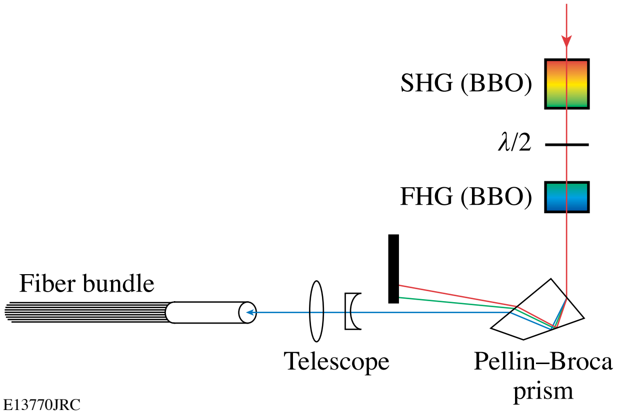

Figure 103.37
A block diagram of UV frequency conversion setup and fiber bundle launching.

Experimental Results

The double-pass amplifier must be heavily saturated in order to achieve high efficiency. To compensate for gain saturation, the ODR+ timing is set such that a switch-in Pockels cell shapes the first three to four pulses of the injected comb, decreasing their amplitudes. Even with this precompensation, the best pulse shape achieved [Fig. 103.38(a)] does not meet the requirements. After FHG, the first pulse in the comb shows significant reconversion into the fundamental wavelength, which results in two peaks instead of one [Fig. 103.38(b)], making the UV fiducial comb useless.

The ultraviolet comb energy has been measured in each fiber of the 19-fiber bundle [Fig. 103.39(a)]. On average, it is 4× higher than the requirement; therefore, the gain of the system can be reduced to avoid comb envelope distortion. With the two-pass amplifier off and the IR beam resized for efficient FHG, the energy requirement has been met [Fig. 103.39(b)]. Fourth-harmonic generation efficiency of over 30% has been observed without any sign of reconversion.

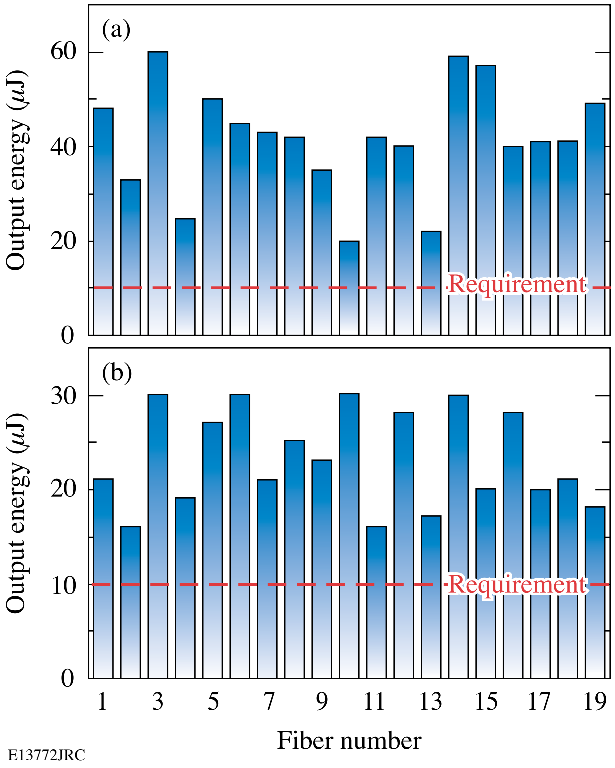

Figure 103.39
The double-pass amplifier produces, on average, 4× more energy than required at the fiber-bundle output (a). ODR+ delivers enough energy to meet the requirement (b).

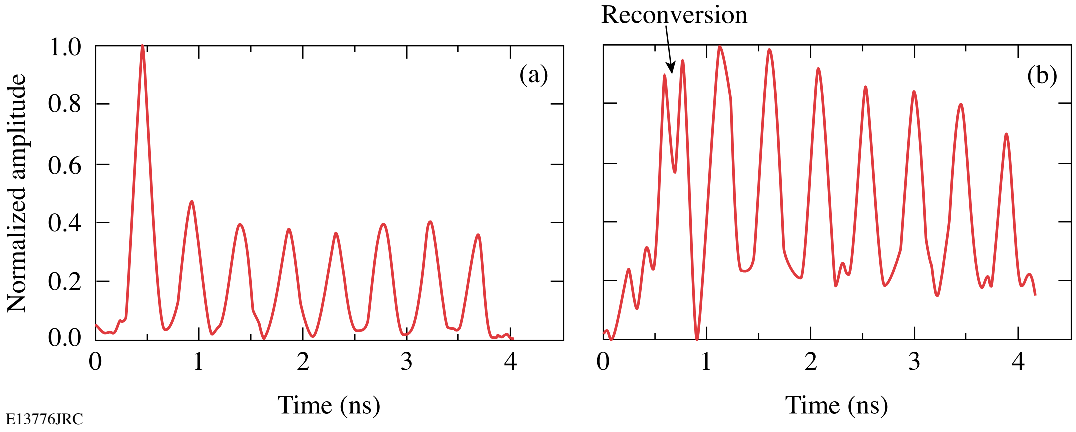

Figure 103.38
Double-pass amplifier IR output (a) and UV comb (b) pulse shapes. The first pulse in the UV comb shows significant reconversion of UV energy.

The fiducial comb injected into the ODR [Fig. 103.40(a)] has been precompensated such that both the green [Fig. 103.40(b)] and UV fiducials [Fig. 103.40(c)] meet the amplitude requirement. Fiducial laser system performance parameters have been measured over three days of operation. Figure 103.41 shows the stability of a UV fiducial comb in one of the fibers over three days; the peak pulse shape stability is ~2% rms. The UV energy stability is 1.5% rms over the same period of time.

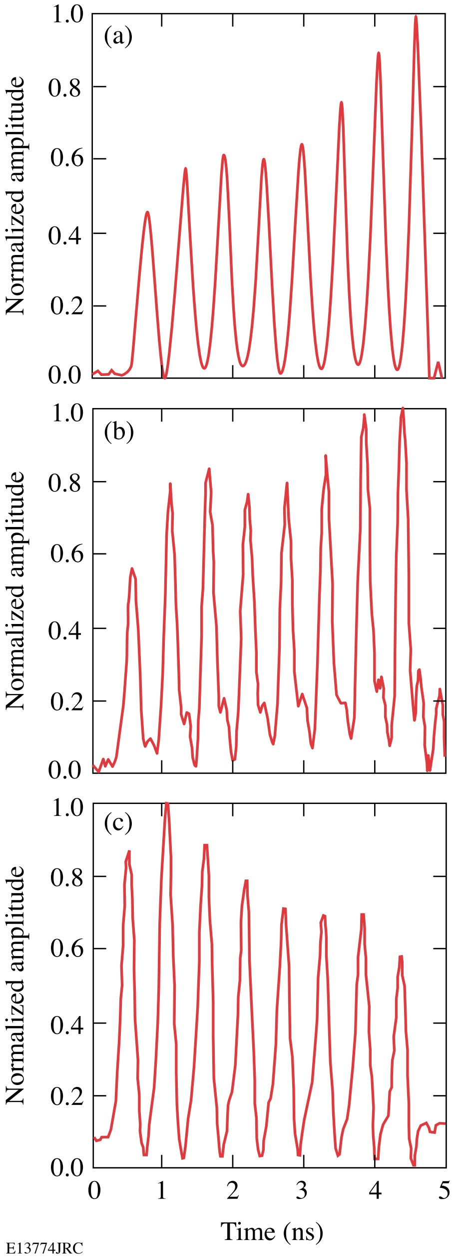

Figure 103.40
The ODR injection fiducial comb (a) is precompensated such that the green (b) and UV (c) fiducials satisfy the requirements.

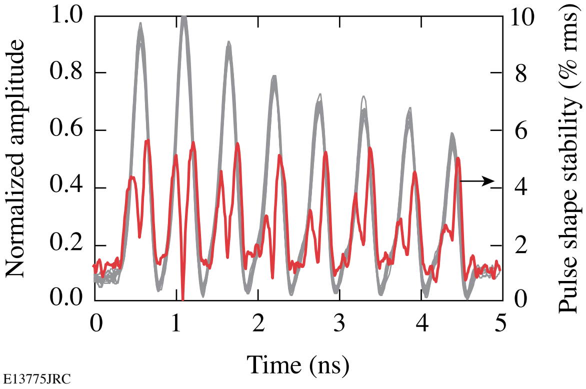

Figure 103.41
The UV fiducial peak pulse-shape stability is ~2% rms, and the energy stability is 1.5% rms over three days of operation.

Conclusion

An efficient, all-solid-state, diode-pumped fiducial laser system that produces IR, green, and UV fiducial combs for the OMEGA diagnostics timing reference has been developed, built, tested, and optimized. All requirements have been met. Excellent beam profile, high energy, and pulse-shape stability have been demonstrated. The turn-key system improves reliability compared to the existing flash-lamp–pumped system and has a smaller footprint of 4 × 5 ft.

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