Unique High-Bandwidth, UV Fiber Delivery System for OMEGA Diagnostics Applications

Introduction

The OMEGA laser at the Laboratory for Laser Energetics was built for direct-drive inertial confinement fusion (ICF) experiments.[1] Sixty symmetrically disposed laser beams are used to compress ICF capsules that typically contain deuterium–tritium (DT) or deuterium. The laser beams heat and compress the target, causing the fuel to undergo thermonuclear fusion. Special temporally shaped pulses, which typically have a 1- to 3-ns duration, must be generated to optimize the target compression. To avoid hydrodynamic instabilities during the target compression the target illumination must be highly uniform.[2] This requires good power balance of all 60 OMEGA beams. The characteristic time of the hydrodynamic instability seed is under 100 ps, which means that the laser drive must be uniform on a 100-ps time scale. This defines the time scale over which power balance must be achieved.[3]

To measure the UV pulse shape and OMEGA power imbalance (see Fig. 85.29), we developed a ten-channel streak camera based on a commercial P510 streak tube.[4] Six such cameras are used to measure the pulse shape in the 60 OMEGA beams.

Motivation

High fusion neutron yield produced during OMEGA target shots causes excessive noise in the streak camera's charge-coupled devices (CCD's), significantly reducing the camera's dynamic range. The neutron-induced noise could be reduced by placing the cameras behind the Target Bay's shield wall. This required the development of a longer fiber optic system to deliver light from the sampling point to the streak camera input.

The most important parameters of the optical fiber to be used in this delivery system are high transmission at the OMEGA working wavelength (351 nm) and low modal dispersion. We require ~15-m-long fibers, so we set our attenuation requirement to ≤220 dB/km at 351 nm. The modal dispersion must be low enough to allow an overall bandwidth of the streak camera diagnostic to be ≥30 GHz.

To assure pulse-shape fidelity of the frequency-modulated and wavelength-dispersed laser pulse,[5] a speckle pattern is launched into the fibers, which is matched to the multimode

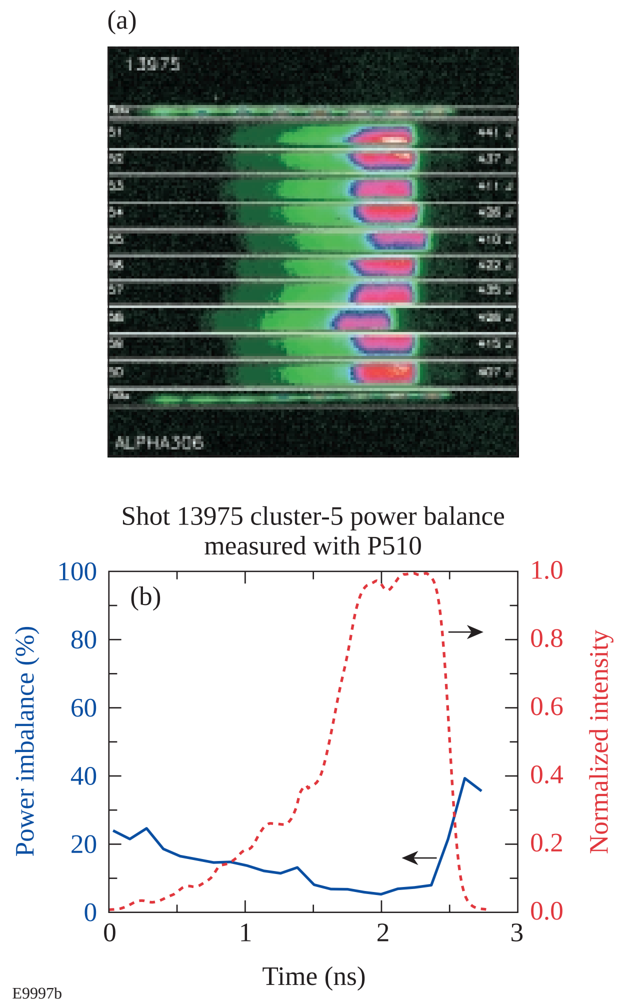

Figure 85.29
P510 streak cameras provide pulse-shape and power-imbalance measurements for all 60 beams of OMEGA. (a) Streak camera recording of all ten beams in one OMEGA cluster. (b) P510 streak camera average pulse shape for all ten beams of cluster 5 on shot 13975 (dashed line) and beam-to-beam power imbalance (solid line) determined from the streak records.

pattern of the fiber. The statistics are further improved by launching into a bundle of seven fibers (Fig. 85.30). To increase the fiber bundle's light-launching efficiency, the ratio of the cladding diameter to the core diameter (clad/core ratio) should be close to 1.

Assembling fiber bundles requires high precision in matching individual fiber lengths. Unequal fiber lengths will reduce the bandwidth of the optical fiber delivery system.

Optical Fiber Manufacturing

Optical fibers were made using the modified chemical vapor deposition (MCVD) method.[6] The 13-mm-diam preforms used consisted of a P_2O_5 doped silica core and a pure silica glass cladding; initial clad/core ratio was 2. Before fiber drawing, the preforms were etched in hydrofluoric acid (HF) to achieve a clad/core ratio of 1.25. The MCVD method ensured the required graded index profile and low dispersion at the working wavelength. Figure 85.31(a) shows the preform's index-of-refraction profile. The central dip in this profile is due to vaporization of P_2O_5 while the preform collapses under high temperature during the preform manufacturing process. While this dip cannot be removed completely, it can be minimized. The presence of the dip did not affect fiber performance. The optical fibers were drawn from preforms and covered in line with an epoxyacrylate coating using a pressurized die. The fibers have a core diameter of 100 μm, a cladding diameter of 125 μm, and a coating diameter of 250 μm. The typical fiber attenuation dispersion curve in Fig. 85.31(b) demonstrates that the optical fiber satisfies the <220-dB/km attenuation requirement at OMEGA's working wavelength.

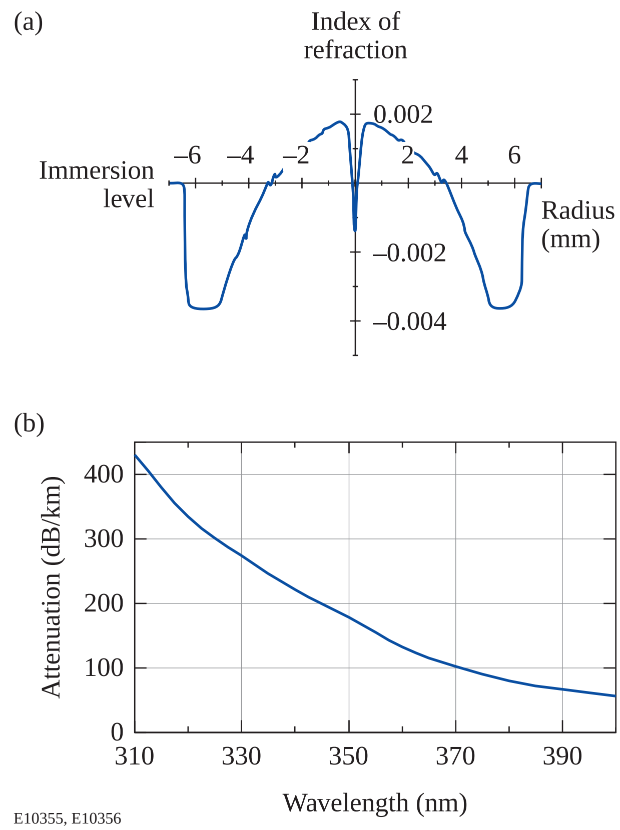

Figure 85.31
(a) Index-of-refraction profile for the fiber preform and (b) the fiber attenuation dispersion curve.

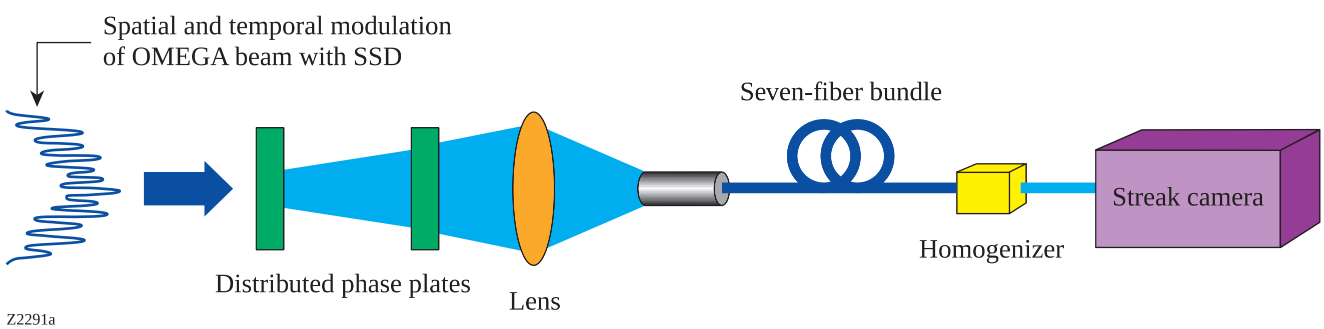

Figure 85.30
Schematic of optical UV fiber delivery system that was designed to sample the OMEGA laser beam and bring the light to the streak camera.

Laser System with Pulse Compression for Fiber Testing

To test the optical fiber and fiber bundle bandwidth, a laser system similar to that described in Ref. 7 was used; it produced 20-ps synchronizable laser pulses at 337-nm wavelength at a ≤10-Hz repetition rate. A block diagram of the laser system is shown in Fig.85.32. Starting with the *Q*-switched Nd:YLF monomode laser, a 10-ns square pulse with ~10-μJ energy was sliced out. After amplification, this pulse was directed to a stimulated Brillouin scattering (SBS) cell filled with CCl_4. By choosing the right focusing geometry and input energy, the incoming 10-ns pulse was compressed to ~360 ps with more than 50% energy efficiency. After second-harmonic conversion the 527-nm pulse was further compressed to ~20 ps using a pressurized-hydrogen, stimulated Raman scattering (SRS) cell (frequency shift is 4156 cm^{-1}). The energy of the SRS 674-nm pulse was >2 mJ; another second-harmonic conversion resulted in a ~20-ps, 337-nm, >0.5-mJ externally synchronizable pulse. The timing jitter of this pulse was measured to be ~150-ps rms. The SBS pulse compression mechanism is the source of this timing jitter. The focused-laser-beam Rayleigh range inside the SBS cell defines the jitter of the compressed pulse because the compression process may start at any point within the Rayleigh range.

A streak camera was used to measure the single-fiber modal dispersion. Single-shot measurements were made, recording the pulse width after its propagation through a 40-m piece of optical fiber compared to propagation through air. The optical-fiber modal dispersion was calculated using the following relationship:

$$\Delta t = \sqrt{\left(t_{\text{out}}\right)^2 - \left(t_{\text{in}}\right)^2} \Big/ L_{\text{fiber}} ,$$

where Δt is the modal dispersion, t_{in} is the fiber input-pulse width, t_{out} is the fiber output-pulse width, and L_{fiber} is the

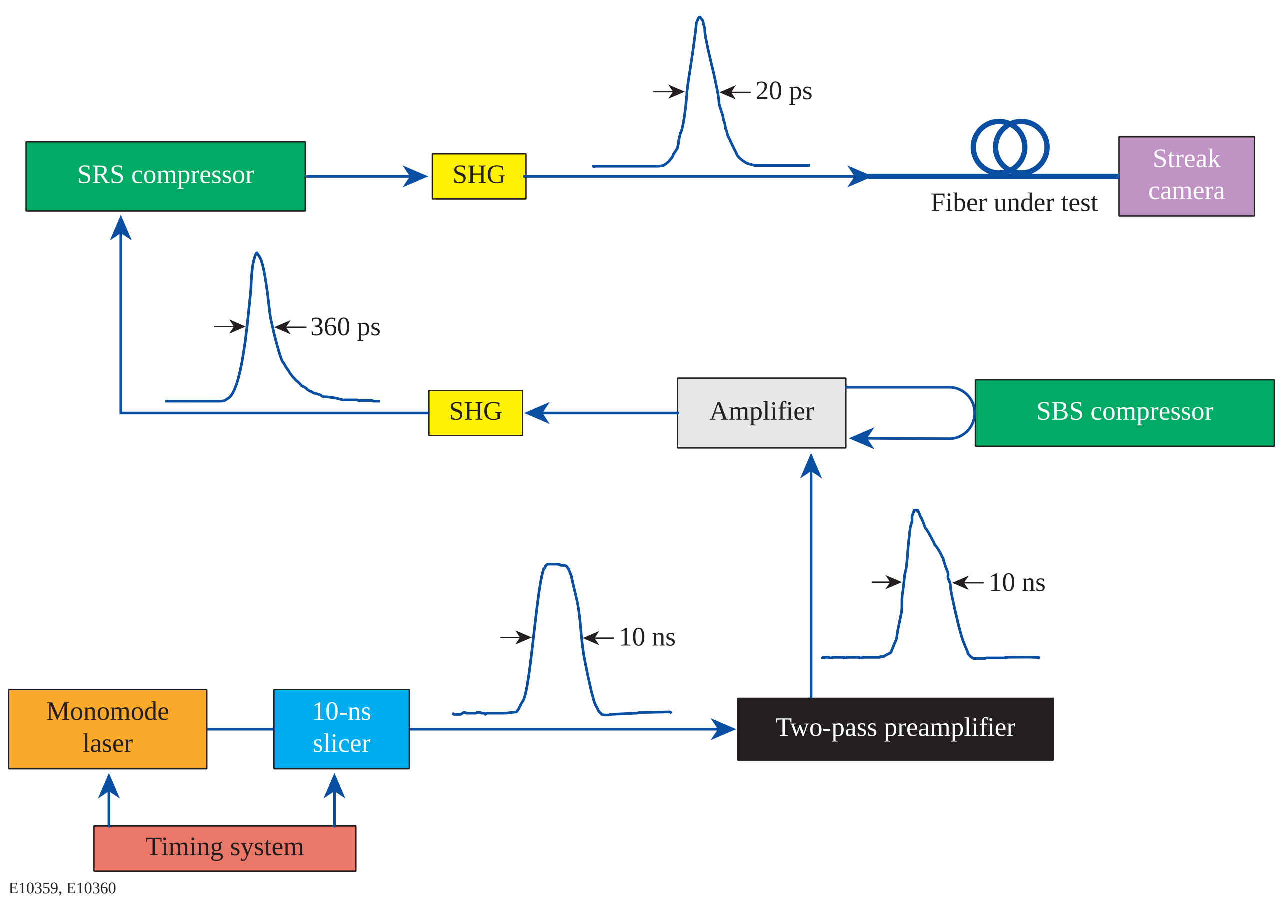

Figure 85.32
Schematic diagram of the SBS–SRS pulse-compression laser system that produces 500× compressed pulse in UV. The system can be externally synchronized.

length of the fiber under test. The modal dispersion was measured to be 0.3 to 0.7 ps/m, depending on the fiber preform. Hence, the single optical fiber bandwidth limited by the fiber modal dispersion is >33 GHz, which satisfies OMEGA requirements. A summary of the optical fiber parameters is shown in Table 85.II.

Table 85.II: Technical characteristics of the optical fiber.

Core diameter	100 μm
Cladding diameter	125 μm
Coating diameter	250 μm
Core/cladding concentricity	2.5 to 3 μm
Cladding/coating concentricity	<10 μm
Core noncircularity	4% to 5%
Cladding noncircularity	1.8% to 2%
Minimum working bend radius	100 mm
Numerical aperture	0.13
Attenuation @ 351 nm	170 to 220 dB/km
Modal dispersion	0.3 to 0.7 ps/m

Fiber Bundle Manufacturing and Testing

The seven-fiber-bundle assembly requires a close matching of the individual fiber lengths. Fiber-length differences will cause a spread in time of the output pulse [see Fig. 85.33(a)], which will degrade the fiber delivery system's bandwidth. Figure 85.33(b) shows the simulated broadening of a 10-ps input pulse in a 15-m seven-fiber bundle with ±1-mm fiber-length differences. In this case, unequal fiber lengths limit the fiber delivery system's bandwidth to ~35 GHz, which is still acceptable for OMEGA applications. The goal was to maintain fiber-length differences within a ±1-mm range for seven 15-m individual fibers. A process was developed that achieved this level in fiber-length accuracy. The process started with a stainless steel tube that accepts seven fibers in a hexagonal close-pack pattern. Fibers were aligned flush with the edge of the tube using a glass slide. Using a microscope, the seven-fiber pattern was rotationally aligned to a key of FC/PC fiber connector to minimize coupling losses when the two fiber bundles were connected. Next, the seven fibers were formed into a fiber ribbon. The fiber ribbon was tensioned, and the fibers were cut flush with the edge of another stainless steel tube installed in the far end. Finally a fiber jacket was placed over the fiber bundle, and the fiber connectors were polished.

Forty fiber bundles were assembled by this method. To characterize the fiber-bundle bandwidth, a pulse propagated through a single 15-m fiber was compared with a pulse propagated through the seven-fiber bundles. Figure 85.34 shows minor spreading of the pulse in the fiber bundles caused by unequal fiber length, demonstrating that the fiber-bundle bandwidth exceeds 50 GHz.

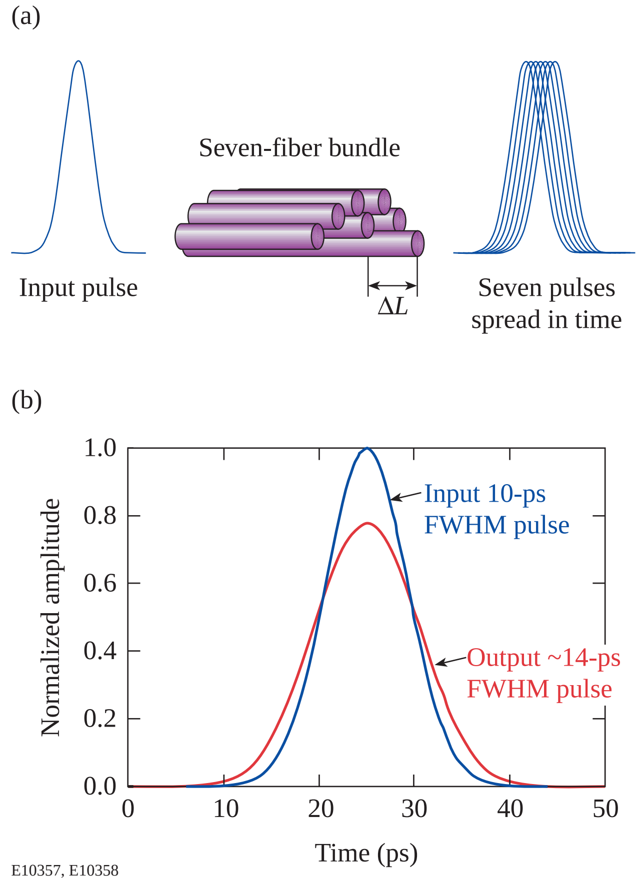

Figure 85.33
(a) A fiber bundle broadens the output pulse because of fiber-length differences that limit the bandwidth of a fiber delivery system. (b) Simulated broadening of a 10-ps pulse in a 15-m fiber bundle when $\Delta L = \pm 1$ mm.

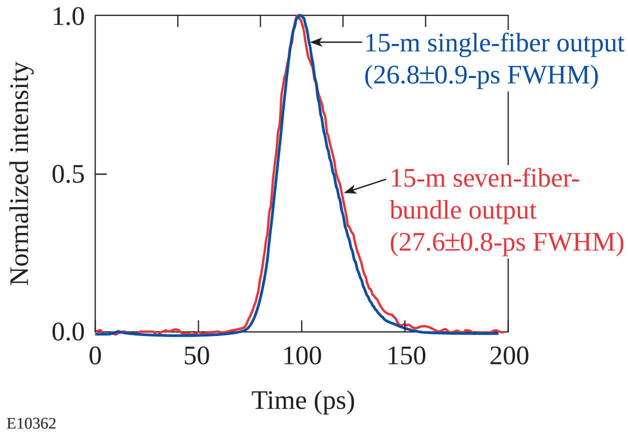

Figure 85.34
Streak camera recording of a pulse propagated through a single fiber is compared with that propagated through a seven-fiber bundle. The seven-fiber-bundle assembly procedure does not limit the bandwidth of the fiber-delivery system.

Conclusion

A special optical fiber for OMEGA laser pulse shape and power imbalance diagnostics was developed and tested. Modal dispersion of less than 1 ps/m was measured for this fiber. A fiber-bundle-assembly procedure was implemented that provides better than ±1-mm fiber length matching over a 15-m fiber length. The fiber delivery system based on these bundles has more than 30-GHz bandwidth and high transmission at 0.35-μm wavelength.

ACKNOWLEDGMENT

The high-bandwidth, UV-transmitting, graded-index optical fiber for this fiber delivery system was developed by the Vavilov State Optical Institute, St. Petersburg, Russia, for use in laser diagnostics on the NIF laser. Funding was provided by Lawrence Livermore National Laboratory. This work was supported by the U.S. Department of Energy Office of Inertial Confinement Fusion under Cooperative Agreement No. DE-FC03-92SF19460, the University of Rochester, and the New York State Energy Research and Development Authority. The support of DOE does not constitute an endorsement by DOE of the views expressed in this article.

REFERENCES

1. T. R. Boehly, R. S. Craxton, T. H. Hinterman, P. A. Jaanimagi, J. H. Kelly, T. J. Kessler, R. L. Kremens, S. A. Kumpan, S. A. Letzring, R. L. McCrory, S. F. B. Morse, W. Seka, S. Skupsky, J. M. Soures, and C. P. Verdon, Fusion Technol. **26**, 722 (1994).
2. J. M. Soures, R. L. McCrory, C. P. Verdon, A. Babushkin, R. E. Bahr, T. R. Boehly, R. Boni, D. K. Bradley, D. L. Brown, R. S. Craxton, J. A. Delettrez, W. R. Donaldson, R. Epstein, P. A. Jaanimagi, S. D. Jacobs, K. Kearney, R. L. Keck, J. H. Kelly, T. J. Kessler, R. L. Kremens, J. P. Knauer, S. A. Kumpan, S. A. Letzring, D. J. Lonobile, S. J. Loucks, L. D. Lund, F. J. Marshall, P. W. McKenty, D. D. Meyerhofer, S. F. B. Morse, A. Okishev, S. Papernov, G. Pien, W. Seka, R. Short, M. J. Shoup III, M. Skeldon, S. Skupsky, A. W. Schmid, D. J. Smith, S. Swales, M. Wittman, and B. Yaakobi, Phys. Plasmas **3**, 2108 (1996).
3. W. R. Donaldson, R. Boni, R. L. Keck, and P. A. Jaanimagi, in *Optical Pulse and Beam Propagation*, edited by Y. B. Band (SPIE, Bellingham, WA, 1999), Vol. 3609, pp. 121–127.
4. P510PSU streak tube, Philips Photonics, Slatersville, RI 02876.
5. S. Skupsky, R. W. Short, T. Kessler, R. S. Craxton, S. Letzring, and J. M. Soures, J. Appl. Phys. **66**, 3456 (1989).
6. S. R. Nagel, J. B. MacChesney, and K. L. Walker, IEEE J. Quantum Electron. **QE-18**, 459 (1982).
7. R. R. Buzyalis *et al.*, Sov. J. Quantum Electron. **17**, 1444 (1987).