clear understanding of the importance of small-scale phase structures to the irradiation uniformity on target.

ACKNOWLEDGMENT

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2.B En Route to the Petawatt

Short-Pulse Amplification: the CPA Concept

In order to amplify short optical pulses, three major requirements have to be fulfilled by the amplifying medium. First, the bandwidth of the amplifier must be large enough to accommodate the full spectrum of the short pulse. Second, to efficiently extract the energy stored in the amplifier, the fluence of the pulse has to be near the saturation fluence of the medium $F_s = h\nu/\sigma$, where σ is the stimulated emission cross section. Finally, the intensity within the amplifier has to stay below a critical level at which nonlinear effects become significant and distort the spatial and temporal profiles of the pulse. The integrated nonlinear index along the optical path is given by the B integral[1]:

$$B = \frac{2\pi}{\lambda} \int \frac{\Delta n}{n}\, dl = \frac{2\pi}{\lambda} n_2 \int_o^L I(z) dz \ . \qquad (1)$$

The B integral at any position across the beam gives the amount of phase delay experienced by the high-intensity beam. The critical intensity corresponds to a B value of the order of 5. Above this value, the high spatial frequencies are preferentially amplified and must be removed by spatial filtering. In the case of dyes and solid-state media, this leads to a critical intensity of the order of 10 GW/cm^2.

Typically, dye and excimer systems are used to amplify short pulses. These media have broad bandwidths of the order of 20 nm, which can support pulse widths as short as 30 fs. However, these media have low saturation fluence levels of millijoules per square centimeter. One-hundred-femtosecond pulses can be amplified to the saturation level without reaching prohibited peak powers and generating unwanted nonlinear effects. Dye amplifiers are therefore well suited for amplification of short pulses to the millijoule level. Further amplification of these pulses has been accomplished with excimer amplifiers[2] by scaling up the amplifier aperture.

As shown above, low saturation fluence combined with a short storage time of a few nanoseconds makes dyes and excimers less than ideal amplifier media. By using an amplifying medium with a thousand times larger saturation fluence, joule energies can be reached with a tabletop-sized system. For example, solid-state media doped with neodymium, chromium, or titanium typically have a saturation fluence of the order of 5 J per square centimeter. Furthermore, they can accept doping concentrations higher than 5×10^{20} atoms per cubic centimeter. Chromium-doped crystals have already shown lasing capabilities from 100 nm to 1100 nm with large bandwidths. One of them, alexandrite, with a bandwidth covering the 700-nm to 800-nm range, has reached a high-average-power performance of 100 W.[3] Another very promising medium is titanium-sapphire, which has been reported to lase between 700 nm and 1000 nm. A well-developed and widely used solid-state amplifier is neodymium glass. With a bandwidth larger than 20 nm, it can support the amplification of 100-fs pulses. However, if we amplify a 1-ps pulse to the saturation level, the power density becomes of the order of TW/cm^2, well above the critical intensity level. Because of the peak intensity limitation, the large amount of stored energy in this medium cannot be extracted. For this reason, solid-state lasers have been primarily used for long (nanosecond) pulse amplification, rather than for the amplification of picosecond pulses.

A new technique is necessary to amplify short pulses to saturation energies while maintaining a low power level in the amplifier. We have developed such a technique using chirped pulse amplification (CPA); it is illustrated in Fig. 31.23: a short optical pulse is initially chirped and stretched, allowing it to be amplified to saturation while maintaining relatively low peak power. After amplification, an optical compressor is used to restore the original short pulse width, producing a pulse with short duration and large energy.

There are two methods for expanding and compressing the optical pulses. The first method uses the fiber-grating compression technique, as will be shown in the next section. The second method uses a grating pair, for both stretching and compressing, and will be described at the end of this article.

Generation of 0.5-TW, 1-ps Pulses

As has been previously reported, we have demonstrated the CPA technique using a fiber-grating compression system.[5,6] The original CPA system employed a Nd:YAG oscillator and silicate glass amplifiers to produce 100-mJ pulses with durations of 2 ps. Presently we are using a cw-pumped mode-locked Nd:YLF laser, which

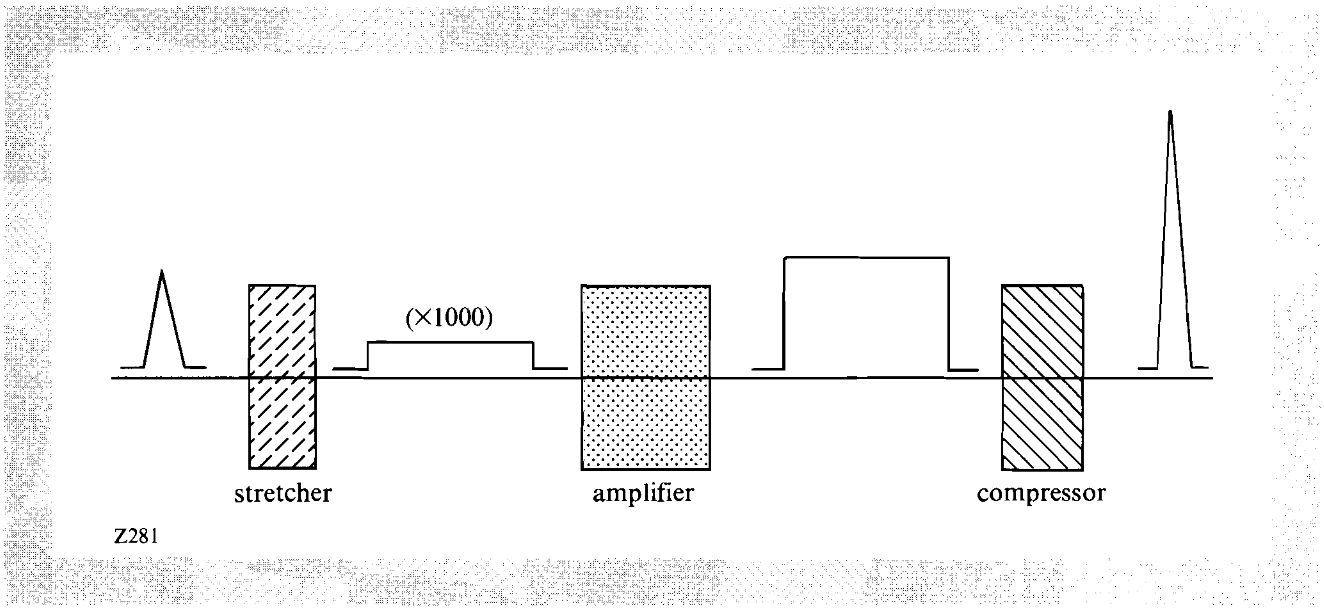

Fig. 31.23
Chirped-pulse amplification technique.

produces 55-ps pulses and therefore allows shorter compressed pulse widths.[7] Another advantage of Nd:YLF is that its wavelength matches that of phosphate Nd:glass amplifiers, which have better thermal properties than silicate glass. The current CPA system generates 0.5-TW pulses of 1-ps duration.

A schematic of the laser system is shown in Fig. 31.24. A cw-pumped mode-locked Nd:YLF oscillator generates a 100-MHz train of 55-ps pulses at a wavelength of 1.053 μm. The pulses are coupled into a 9-μm core, 1.3-km single-mode optical fiber. Due to both self-phase modulation and group velocity dispersion (GVD), the pulses are linearly chirped to 300 ps across a 3.5-nm bandwidth.[8] At this point, the pulses can be compressed to 1 ps using a double-pass grating compressor, as shown in Fig. 31.25.[9] With the CPA technique, the chirped (300-ps) pulses are first amplified and then compressed. By using this technique, 300 times more energy can be extracted than by directly amplifying a compressed 1-ps pulse.

The chirped pulses are amplified in phosphate Nd:glass (Kigre Q98), whose fluorescence peak at 1.053 μm matches the oscillator wavelength. Its bandwidth (21 nm) allows for amplification of 100-fs pulses. Joule energies are achieved using three flash-lamp-pumped amplifiers. A schematic of the amplification stage is shown in Fig. 31.26. The first stage is a regenerative amplifier operating at 5 Hz. The pulse undertakes ~100 round trips to reach saturation in a linear cavity containing a 7-mm-diameter rod before being switched out. At this stage, the pulse energy has been increased by more than six orders of magnitude, from 1 nJ to 2 mJ. After upcollimation, the pulse is amplified to 100 mJ in a four-pass, 9-mm-diameter amplifier. The pulse is then upcollimated a second time and spatially filtered before being amplified in the third stage. This final stage consists of a 16-mm-diameter rod used in single pass, which brings the energy level of the pulse to over 1 J.

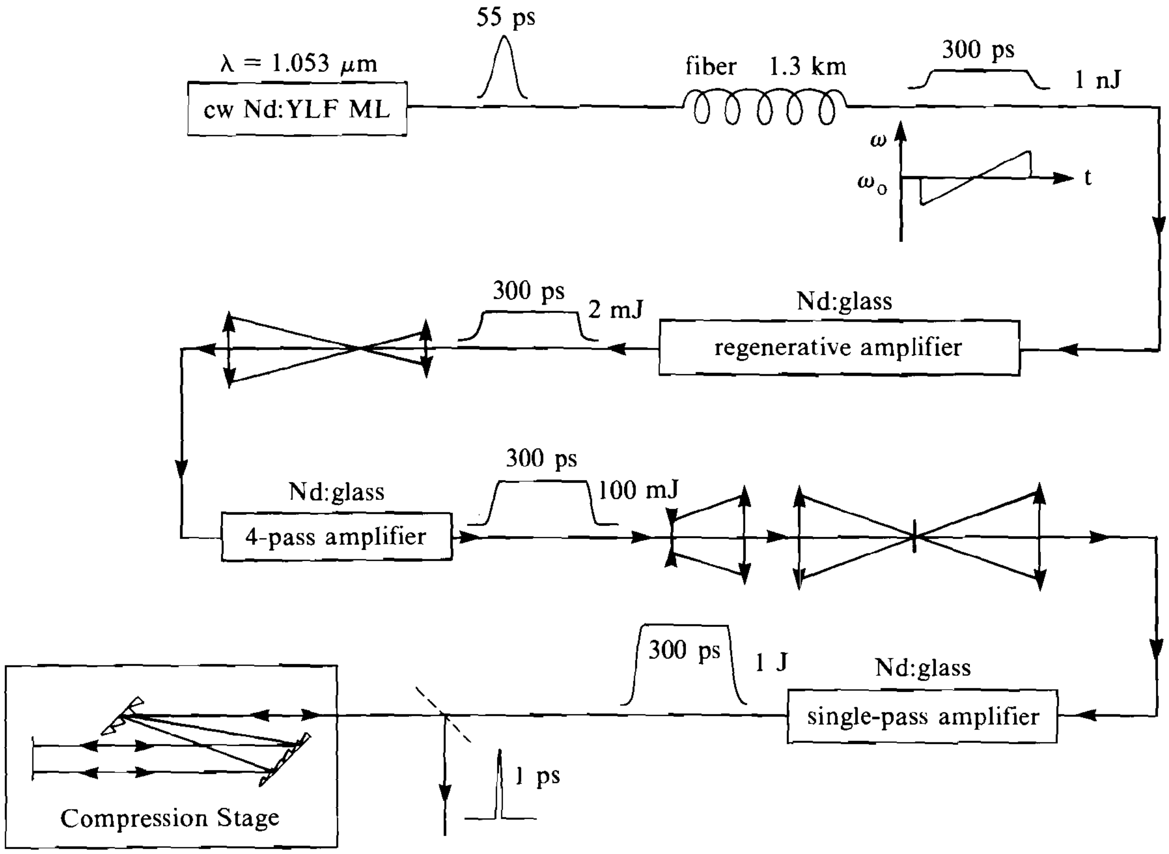

Fig. 31.24
Diagram of the current laser system.

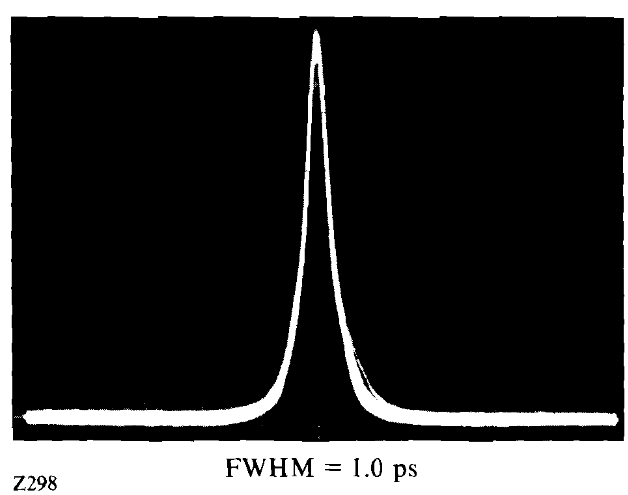

Fig. 31.25
Autocorrelation trace of the compressed Nd:YLF, showing a pulse width of 1 ps assuming a Gaussian profile.

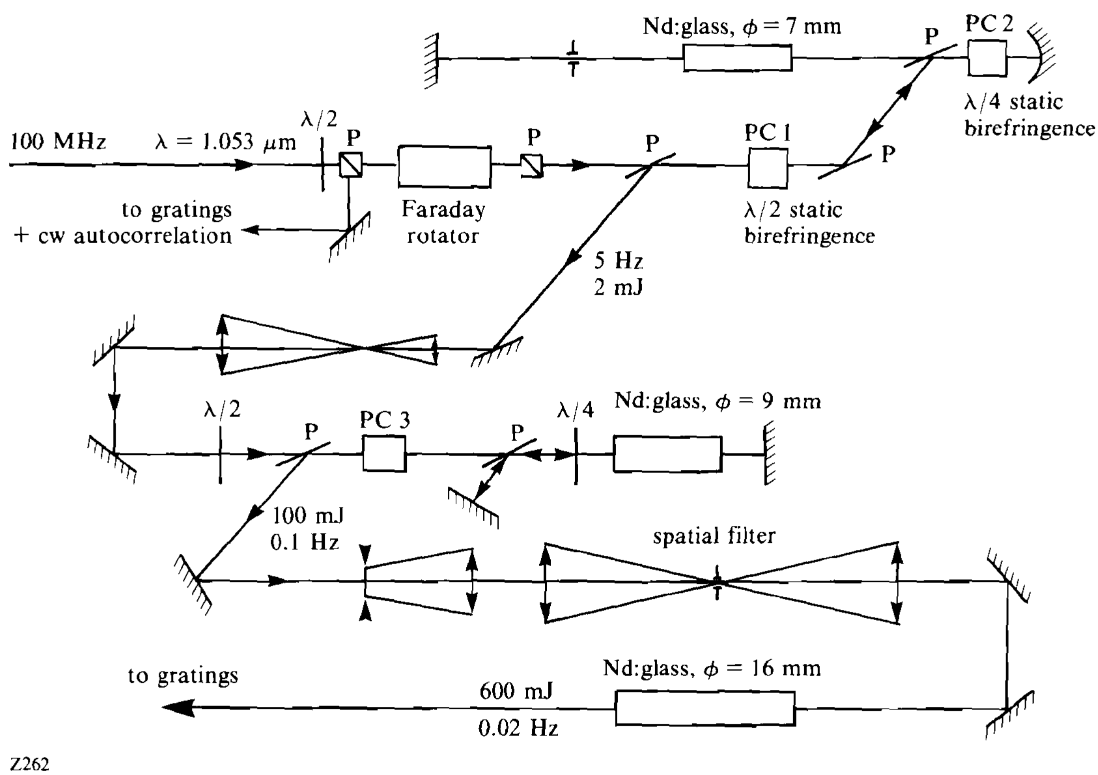

Fig. 31.26
Schematic of the amplification stage.

The compression stage consists of two gold-coated holographic gratings with 1700 ℓ/mm that are used in near-Littrow configuration. The single-pass efficiency of the compression stage is 90% for *p*-polarized light. In order to operate below the damage threshold of the gratings (~ 100 mJ/cm^2), a conservative value of 20 mJ/cm^2 on the grating has been adopted. Therefore, only 500 mJ can be incident on our current gratings, which have dimensions of 7 × 7 cm^2. To have maximum pulse energy, we use the compressor in a single-pass configuration.

The pulse-width measurement was carried out using a single-shot autocorrelator based on noncollinear second-harmonic generation.[10] A schematic of the apparatus is given in Fig. 31.27, and the autocorrelation trace is shown in Fig. 31.28. Assuming gaussian profile, the pulse width is 1-ps FWHM. This yields a 0.5-TW pulse at output of the system, the repetition rate of which is limited by the power conditioning of our 16-mm amplifier to one shot every 50 s. Slab amplifiers could be operated faster than 1 Hz.

We have recently measured the beam divergence of the compressed pulse at the 1-mJ level (with only the first amplifier), and at 250 mJ (with the three amplifiers), using a long focal lens (5 m) and a detector array. Results show the 1-mJ, 1-ps pulse to be 1.4 times diffraction limited, making possible intensities greater than 10^{16} W/cm^2 with an

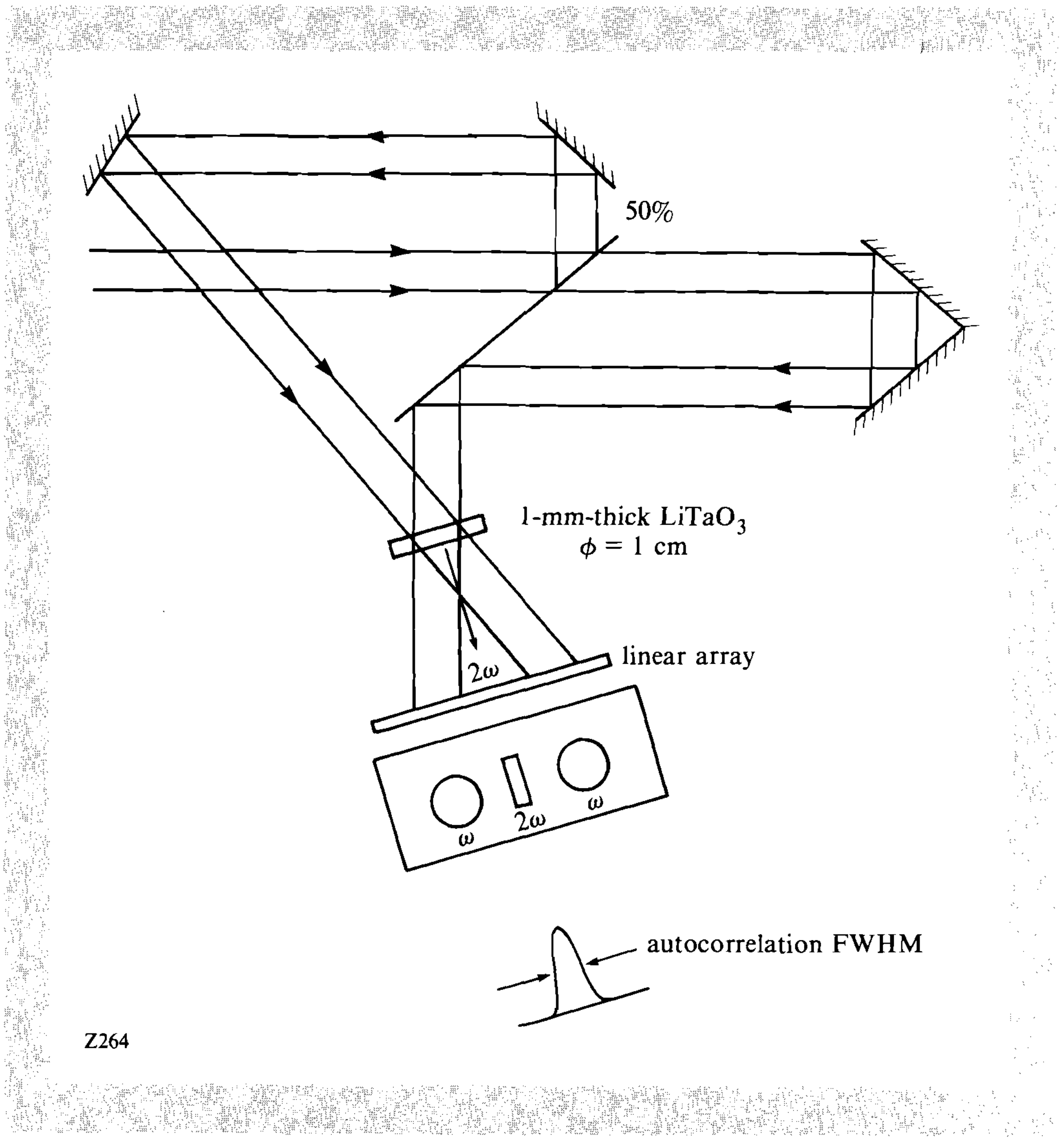

Fig. 31.27
Single-shot autocorrelator.

f/1 lens. Measurements done for the 250-mJ pulses show a 2.2 times diffraction-limited focal spot. This will yield, when focused with an *f*/1 lens, intensities greater than 10^{18} W/cm^2. We attribute the discrepancy between the two focal-spot measurements to a defocusing aberration induced by the thermal lensing of the 16-mm amplifier, most of which could be compensated by proper relocation of the target plane.

To our knowledge, this represents the highest brightness ever achieved. The system needed to generate this performance is remarkably compact: the amplification system that brings the pulse to the joule level stands easily on a 4′ × 8′ table. Furthermore, it has yet to be optimized, and a longer stretched pulse (1 ns) in conjunction with larger gratings will allow us to extract 3 to 4 J out of the last amplifier, while compression optimization will lead to a final pulse of approximately 500 fs. These modifications should produce a peak power of ~6 TW without degrading the focusability, making possible intensities greater than 10^{19} W/cm^2.

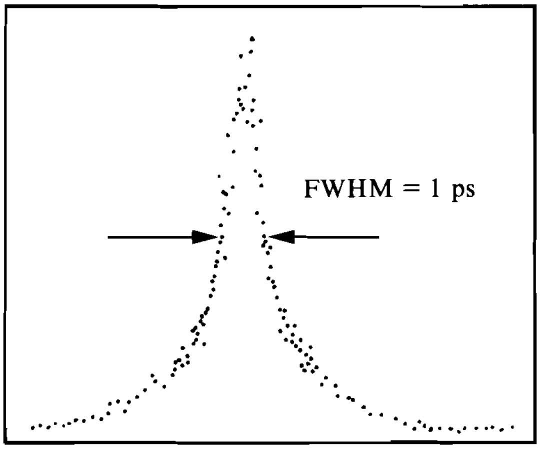

Fig. 31.28
Autocorrelation trace of the 500-mJ pulse, showing a pulse width of 1 ps assuming a Gaussian profile.

Toward Higher Peak Power: the Expansion-Compression Approach

In order to fully exploit the potential of CPA, it is desirable to have the largest ratio between the chirped and compressed pulses. The use of a fiber-grating system for the chirping and subsequent compression imposes certain constraints and limitations on the achievable ratio of the chirped-pulse duration to the compressed-pulse duration r. Single-stage compression of cw mode-locked YAG or YLF is limited to approximately an r of 300. This limitation stems from the nonlinear relationship of the group delay versus wavelength for a grating pair. The delay between spectral components arising from dispersion within the fiber can only be compensated by a grating pair to the first order.

The group time delay $\tau = d\rho/d\omega$ from a grating pair in double pass can be written to the second order as[11]

$$\tau(\lambda_o+\Delta\lambda) = \tau_o + 2\frac{\lambda_o}{c} L \frac{m^2}{a^2\cos^3\theta}\Delta\lambda + \frac{3L\, m^2}{c\, a^2 \cos^3\theta}\left(1 + \frac{\lambda_o m \sin\theta}{a\cos^2\theta}\right)(\Delta\lambda)^2$$

$$= \tau_o + \tau_1 + \tau_2 \ , \qquad (2)$$

where $\lambda = \lambda_o + \Delta\lambda$ is the wavelength, λ_o the central wavelength of the pulse, c the speed of light, L the distance between the planes containing the gratings, m the diffraction order, a the line spacing, and θ the diffracted angle.

A linearly chirped pulse can then be compressed by adjusting the grating parameters to cancel the first-order term, leaving the pulse with a residual chirp described by τ_2. We have simulated the autocorrelation and temporal profile of such a compressed pulse for parameters appropriate to our system. Figure 31.29 demonstrates the effect of τ_2 as the chirped-pulse duration increases, while bandwidth remains constant. The grating spacing has been chosen to cancel τ_1. Increased side lobes are seen in the autocorrelation function, while the FWHM is only marginally affected. The temporal profile shows a more severe effect, where a quadratic delay induces a beating between wavelengths symmetrically displaced with respect to the central wavelength. This leads to a strongly modulated temporal profile (Fig. 31.30). Measurements done with a cw mode-locked Nd:YAG coupled into a 2.4-km fiber show the importance of the quadratic term: when using the entire 4-nm spectrum, the autocorrelation indicates a pulse width of 1.2-ps FWHM, but it exhibits a large pedestal (Fig. 31.31). Using an 0.8-nm interference filter—leaving all other parameters identical—results in a very clean 2-ps pulse (Fig. 31.32). Shorter compressed pulses could also be obtained by using a two-stage compression system. This would not help in bringing about higher peak powers because the chirped pulse the amplifier sees will also be substantially shorter. It is also possible to obtain longer chirped pulses by using a longer optical fiber. This is not a viable alternative, however, because the longer fiber affects the linearity of the chirped pulse and will negatively affect the quality of the compressed pulse.

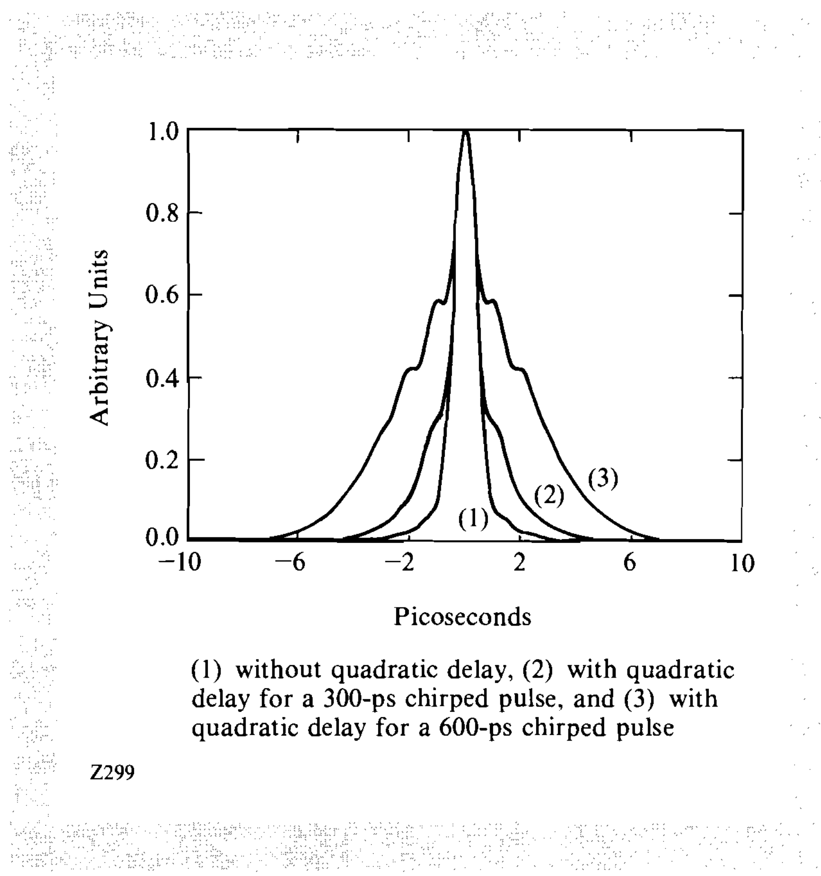

Fig. 31.29
Autocorrelation of compressed/chirped pulses.

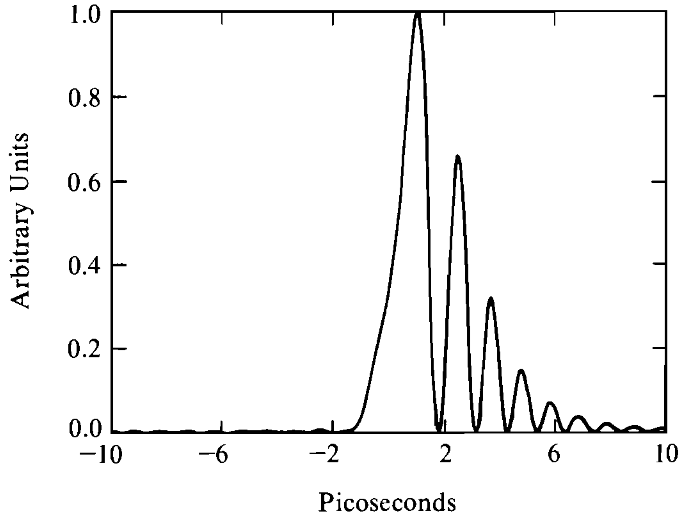

Fig. 31.30
Temporal profile resulting from the compression of a 600-ps chirped pulse.

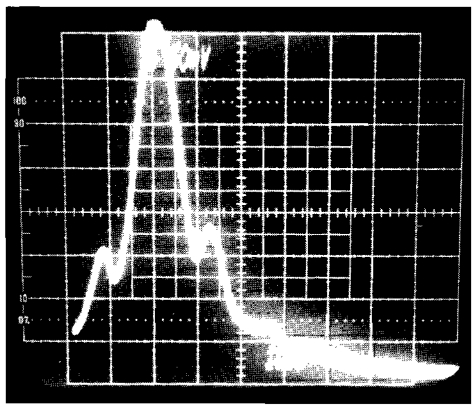

Fig. 31.31
Autocorrelation trace of a 40-Å-bandwidth compressed pulse.

Both simulation and experiments clearly show the limitation of fiber-grating compression for the CPA technique that arises from the mismatch of the dispersive properties of the fiber and the grating pair. The same problem is encountered in the compression of femtosecond pulses. Brito-Cruz was able to overcome this and generate 6-fs pulses by using a combination grating and prism compressor.[12] This solution is not applicable here; prisms are not dispersive enough to yield reasonable physical dimensions in the picosecond domain. However, it is possible to use gratings to do both the compression and expansion.

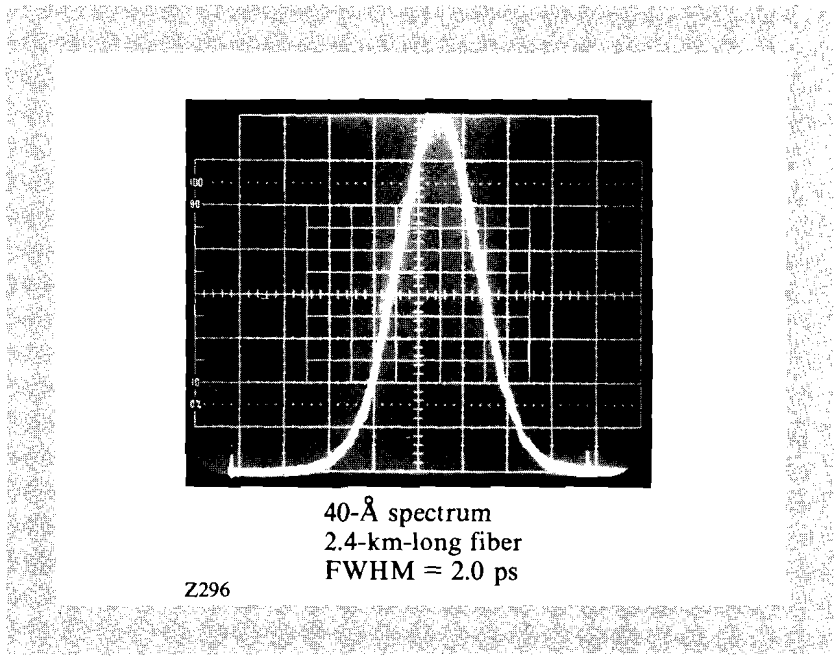

Fig. 31.32
Autocorrelation trace of a filtered 8-Å-bandwidth compressed pulse.

The source used for these experiments was a synchronously pumped, colliding-pulse, mode-locked antiresonant ring dye laser,[13] which delivers 80-fs pulses at a 100-MHz repetition rate. The bandwidth of the laser was 48 Å (FWHM), centered at 617 nm.

The experimental arrangement for both stretching and recompressing the pulse is shown in Fig. 31.33. Two 1700-ℓ/mm reflection gratings are arranged in an antiparallel configuration with a separation of 128 cm, with the laser beam incident about 10° away from Littrow. Between the grating pair, and nearly symmetric with respect to the gratings, are two 500-mm-focal-length lenses separated by 1 m to form a telescope with unit magnification. A corner reflector is used to double-pass through the system, both for compactness and to keep a circular beam profile.

As shown by Martinez,[14] the telescope inverts the angular dispersion, resulting in a net-positive group-velocity dispersion provided that the gratings lie inside the focal planes of the lenses. The effective separation contributing to the dispersion (single pass) is then given by the sum of the distances from each grating to the adjacent focal plane—72 cm for the above arrangement.

The input pulse to the system was measured by the standard second-harmonic-generation autocorrelation method to be 83-fs long (assuming a sech^2 pulse shape). Figure 31.34 shows a synchroscan streak-camera image of the pulse after propagation through the first grating pair. The pulse duration is measured to be 85-ps long, more than 1000 times its original length. As expected from a linearly dispersive system, the pulse shape still resembles a sech^2 and does not square off, as in the standard fiber-grating compression technique.

Like a pulse chirped by self-phase modulation, the stretched pulse now has a positive frequency sweep and can be compressed by another

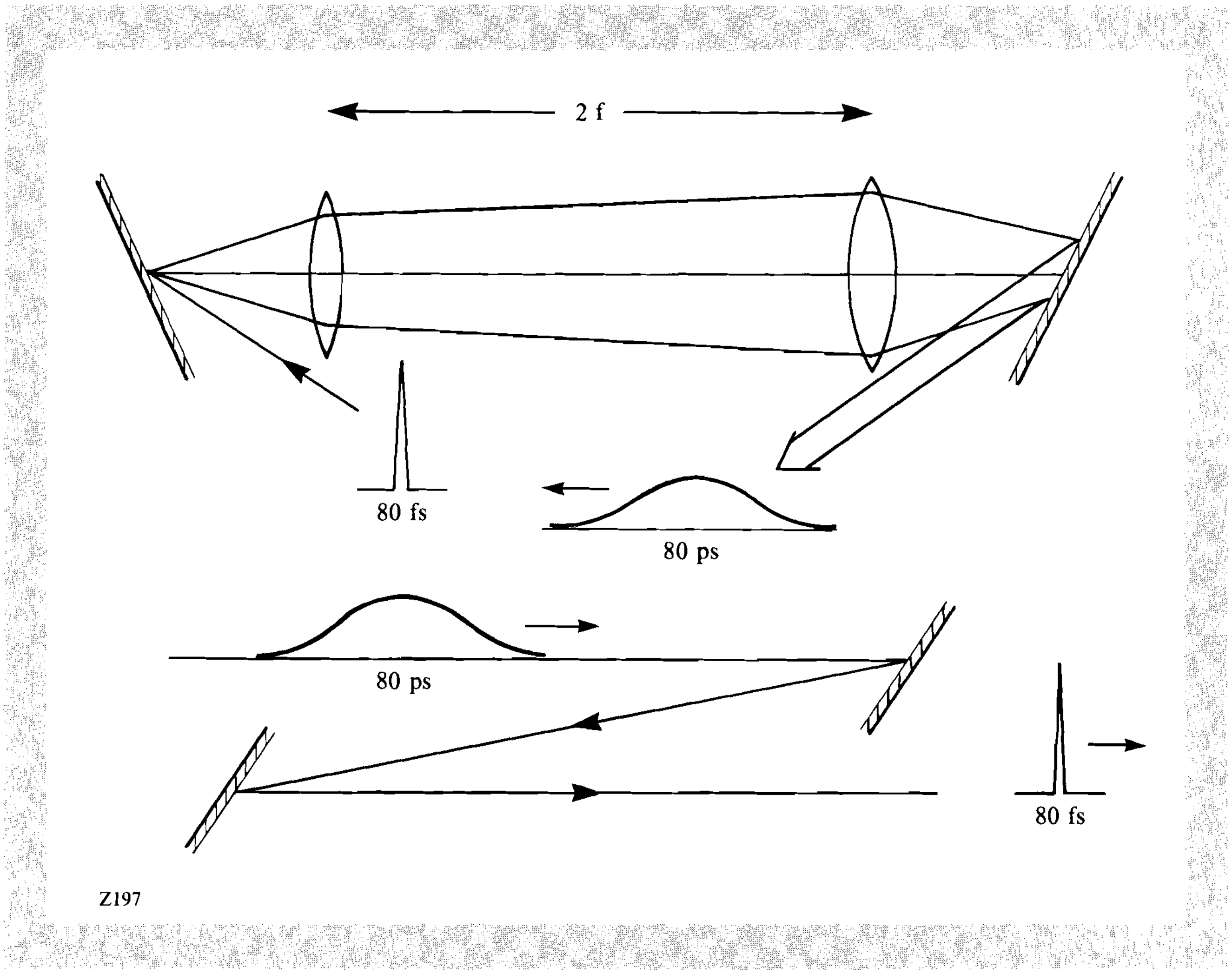

Fig. 31.33
Expansion-compression setup.

pair of gratings. Because the initial chirp was produced by a pair of gratings, it becomes possible to completely compensate for the positive chirp and restore the pulse to its original duration. A pulse that has been linearly chirped in a fiber sees a limitation, due to the fact that the variation of group delay with frequency for a grating pair is not exactly linear. For a linearly chirped 85-ps pulse with ~50-Å bandwidth, this residual nonlinearity would limit the compression to ~1 ps. This limitation has been observed in compression of both picosecond and femtosecond pulses.

A second pair of gratings (identical to the first), arranged parallel in a near-Littrow, double-pass configuration separated by 66 cm, is used to compress the pulse back to its original duration. The separation of the second pair of gratings is slightly less than the effective separation of the first pair because of the different angle of incidence of the beam with respect to the grating normal. This results in a different value of the dispersion for each grating pair. After exiting the system, the pulse duration was measured by performing a background-free cross correlation of the output of the system, with a portion of the original pulse in a 200-μm-thick $LiIO_3$ crystal. Figure 31.35 shows a

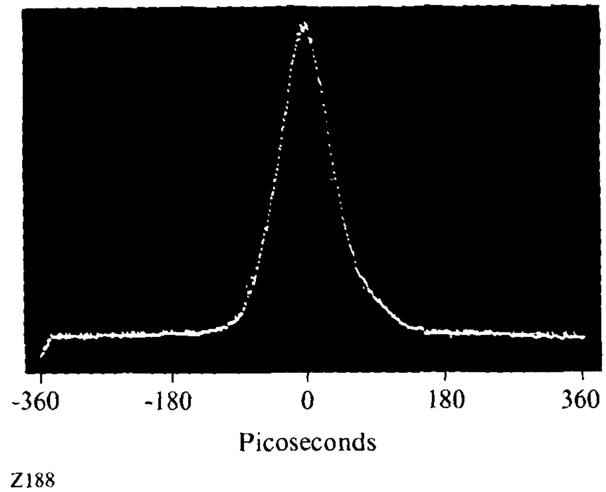

Fig. 31.34
Streak-camera image of pulse after the first grating pair. Pulsewidth (FWHM) = 85 ps. Full sweep = 720 ps.

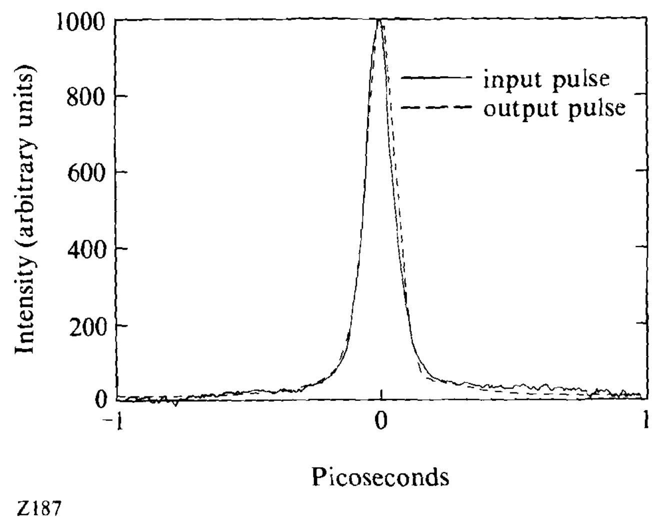

Fig. 31.35
Overlapped autocorrelation trace of the input and output pulses from the expansion-compression stage.

comparison of an autocorrelation of the input pulse and a cross correlation of the input with the output pulse. The measured correlation widths (FWHM) agree to within 10%, showing pulse durations of ~83 fs and 91 fs respectively (again, assuming a sech^2 pulse shape for deconvolution). The difference is attributed to long-term fluctuations in the dye-laser pulse width during the course of the experiment. The traces show a compression factor of ~1000 times, from 85 ps to the 85-fs to 90-fs level.

By using this technique, we are able to completely decouple the duration of the short compressed pulse from the duration of the long chirped pulse. This makes it feasible to consider double-stage compression of the YLF oscillator to generate pulses of the order of 100 fs (a dye oscillator at the proper wavelength would also be suitable). Subsequent expansion to ~ 500 ps prior to amplification would allow us to take full advantage of the bandwidth of the Nd:glass medium. Amplification to the joule level followed by compression will lead to pulses of ~ 1 J/100 fs = 10 TW peak power with our current amplification system.

In conclusion, chirped-pulse amplification has been used to produce single picosecond pulses at the terawatt level. The beam divergence is 2.2 times the diffraction limit, making the brightness of this source greater than 10^{18} W/cm^2 · $\Delta\Omega$, the highest brightness ever reported. Presently, the technique of CPA uses a combination of fiber and grating pair. This technique is limited to a compression of only a few hundred times, due to the higher-order dispersion term in the grating pair. A better embodiment of the chirped-pulse amplification technique uses two grating pairs for pulse expansion and compression. This technique, which has already shown an expansion-compression ratio of 1000, could be improved to obtain an expansion-compression ratio greater than 5000. With the present amplifier, short pulses of a few hundred femtoseconds that were stretched to around 1 ns could be efficiently amplified to a few joules before being recompressed to their initial value, to produce pulses at the 10-TW level with essentially the same-size amplifier system. Even more exciting is the fact that the CPA technique can be used with a very large Nd:glass amplifier, such as the glass development laser at LLE. Approximately 1 kJ can be extracted from this system with a 1-ns pulse. These pulses could then be recompressed to the subpicosecond level, producing pulses well in the petawatt regime. When focused to a few times the diffraction limit, a power density well over 10^{20} W/cm^2 could be achieved.

ACKNOWLEDGMENT

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