Generation of Ultrahigh Peak Power Pulses by Chirped Pulse Amplification

P. MAINE, D. STRICKLAND, P. BADO, M. PESSOT, AND G. MOUROU

(Invited Paper)

***Abstract*—Single picosecond pulses have been amplified to the terawatt level by a table-top size Nd:glass amplifier by using the technique of chirped pulse amplification (CPA). The divergence of the beam is twice the diffraction limit, making the brightness of this source equal to $\sim 2 \times 10^{+18}$ W/(cm · sr), which is the highest brightness ever reported. The technique of chirped pulse amplification allows the efficient energy extraction from extremely compact amplifier systems. Amplification of chirped pulses over nine orders of magnitude, i.e., from nanojoule to the joule level, has been demonstrated. By using a large-scale Nd:glass amplifier system, it should be possible to extend the technique of CPA to the amplification of 1 ps pulse to the kilojoule level leading to petawatt power pulses. These pulses, once focused, could produce intensity in the range of 10^{23} W/cm², five orders of magnitude over the present state of the art.**

I. Short Pulse Amplification: The CPA Concept

In order to amplify short 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, λ_0 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]

$$B = \frac{2\pi}{\lambda} \int \frac{\Delta n}{n}\, dl = \frac{2\pi}{\lambda} n_2 \int_0^L I(z)\, dz.$$

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 on 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 on the order of 10 GW/cm².

Typically, dye and excimer systems are used to amplify short pulses. These media have broad bandwidths on the order of 20 nm which can support pulsewidths as short as 30 fs. However, these media have low saturation fluence levels of millijoules per square centimeter. 100 fs 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 few nanoseconds make dye and excimer poor amplifying media. By using an amplifying medium with a thousand times larger saturation fluence, joule energies can be reached with a table-top sized system. For example, solid-state media doped with neodymium, chromium, or titanium have a saturation fluence on the order of 5 J/cm². Furthermore, they can accept doping concentration higher than 5×10^{20} atoms/cm³. Chromium-doped crystals have already shown lasing capabilities from 700 to 1100 nm with large bandwidths. One of them, alexandrite, with a bandwidth covering the 700–800 nm range, has reached high average power performance of 100 W [3]. Another very promising medium is titanium–sapphire, which has been reported to lase between 700 and 1000 nm. A now well-developed and widely used solid-state amplifier is neodymium–glass which, with a bandwidth larger than 20 nm, should support the amplification of 100 fs pulses. However, if we amplify a 1 ps pulse to the saturation level, the power density becomes on the order of 1 TW/cm², far 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, until now, solid-state lasers have been found well suited for long (nanosecond) pulse amplification, and could not be used efficiently for the amplification of picosecond pulses.

A new technique is necessary to amplify short pulses to saturation energies while maintaining low power levels in the amplifier. In general, our technique to amplify short optical pulses is illustrated in Fig. 1: a short optical pulse

Manuscript received June 16, 1987; revised September 22, 1987. This work was supported by the U.S. Air Force Office of Scientific Research under Contract F49620-87-C-0016 to the Ultrafast Optical Electronics Center, Laboratory for Laser Energetics, University of Rochester, and by the Laser Fusion Feasibility Project, Laboratory for Laser Energetics which has the following sponsors: Empire State Electric Energy Research Corporation, General Electric Company, New York State Energy Research and Development Authority, Ontario Hydro, and the University of Rochester. Such support does not imply endorsement of the content by the above parties.

The authors are with the Laboratory for Laser Energetics, University of Rochester, Rochester, NY 14623.

IEEE Log Number 8718255.

0018-9197/88/0200-0398$01.00 © 1988 IEEE

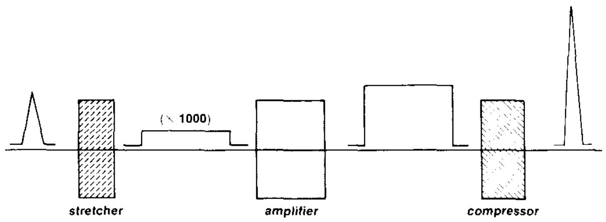

Fig. 1. Chirped pulse amplification technique.

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 pulsewidth, producing a pulse with short duration and large energy.

Two embodiments of the CPA technique have been demonstrated. The first one uses the fiber-grating compression technique, as will be shown in Section II, while the second one utilizes a grating pair both for stretching and compressing and will be discussed in Section III.

II. Generation of 0.5 TW, 1 ps Pulses

As has been previously reported, we have demonstrated the technique of chirped pulse amplification (CPA) using a fiber-grating compression system [5], [6]. Damm *et al.* [4] reported earlier compression of amplified chirped pulses, but were not concerned about nonlinear effects occuring in the amplifier and used a short fiber to avoid group velocity dispersion (GVD), which is counter to the very concept of chirped pulse amplification. At the opposite, the CPA technique requires a *long* chirped pulse, and is based on the optimal use of GVD.

The original CPA system employed an Nd:YAG oscillator and silicate glass amplifiers to produce 100 mJ pulses with durations of 2 ps. Presently, we are using a CW mode-locked Nd:YLF laser which produces 55 ps pulses and therefore allows shorter compressed pulsewidths [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. At present, the current CPA system generates 0.5 TW pulses of 1 ps duration. Terawatt pulses have been reported by Szatmari *et al.* [8] using excimer amplifiers to bring 80 fs pulses to 72 mJ, although to our knowledge, the pulse duration has yet to be measured after amplification.

A schematic of the laser system is shown in Fig. 2. 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 [9]. Because of the low dispersion of silica, the use of a long fiber (1.3 km) is necessary to allow GVD to take place. This will result mainly in two beneficial effects: the lengthening of the chirped pulse, and a high-quality compressed pulse (see, for example, [10]). At this point, the

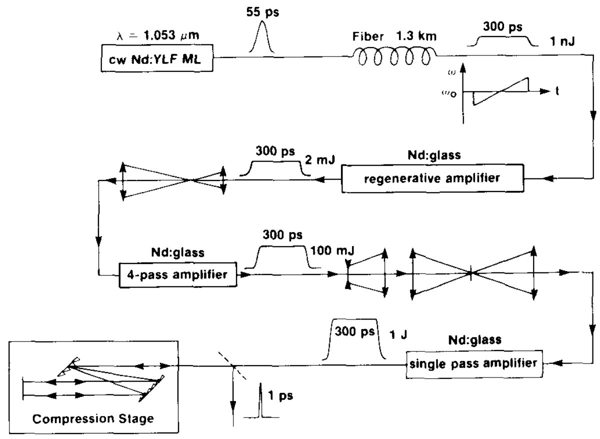

Fig. 2. Diagram of the current laser system.

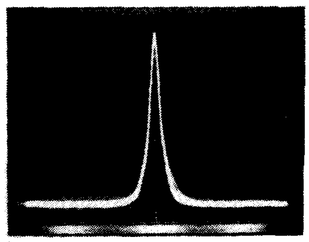

Fig. 3. Autocorrelation trace of the compressed Nd:YLF showing a pulse width of 1 ps assuming Gaussian profile.

pulses can be compressed to 1 ps using a double-pass grating compressor as shown in Fig. 3 [11], [12]. 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 amplifying directly 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 flashlamp-pumped amplifiers. A schematic of the amplification stage is shown in Fig. 4. The first stage is a regenerative amplifier operating at 5 Hz. The pulse undertakes ~ 100 roundtrips 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 up collimation, the pulse is amplified to 100 mJ in a four-pass, 9 mm diameter amplifier. The pulse is then up collimated 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 a joule.

The compression stage consists of two 1700 l/mm gold-coated holographic gratings which are used in near Littrow configuration. The single-pass efficiency of the compression stage is 90 percent for p-polarized light.

In order to operate below the damage threshold of the

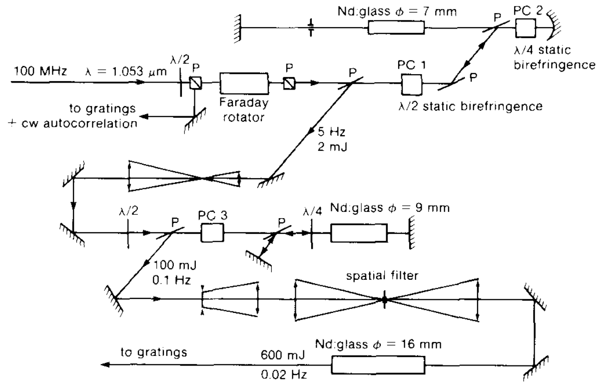

Fig. 4. Schematic of the amplification stage.

gratings (~ 100 mJ/cm^2), a conservative value of 20 mJ/cm^2 of incident flux on the gratings 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. This does not noticeably affect the pulsewidth because of the low ellipticity of the beam (ratio between major and minor axis is 1.6). A calculation conducted after [13] predicts a 5 percent increase in pulsewidth when compared to a double-pass configuration.

The pulsewidth measurement was carried out using a single-shot autocorrelator based on noncollinear second harmonic generation [14], [20]. A schematic of the apparatus is given in Fig. 5 and the autocorrelation trace is shown in Fig. 6. Assuming a Gaussian profile, the pulse width is 1 ps FWHM. This yields a 0.5 TW pulse at the output of the system, the repetition rate of which is limited by the power conditioning of our 16 mm amplifier to 1 shot every 50 seconds (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 the 250 mJ level (with the three amplifiers), using a long focal lens (5 m) and a detector array. Results show the 1 mJ, 1 ps to be 1.4 times diffraction limited, making possible intensities greater than 10^{16} W/cm^2 with an $f/1$ parabola. Measurements done for the 250 mJ pulses show a 2.2 times diffraction-limited focal spot. This will yield, when focused with an $f/1$ parabola, intensities greater than 10^{18} W/cm^2.

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 ft 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 3-4 J out of the last amplifier, while compression optimization will lead to ~ 500 fs final pulse. These modifications should bring a peak power of ~ 6 TW without degrading the focusability, therefore making possible intensities $> 10^{19}$ W/cm^2.

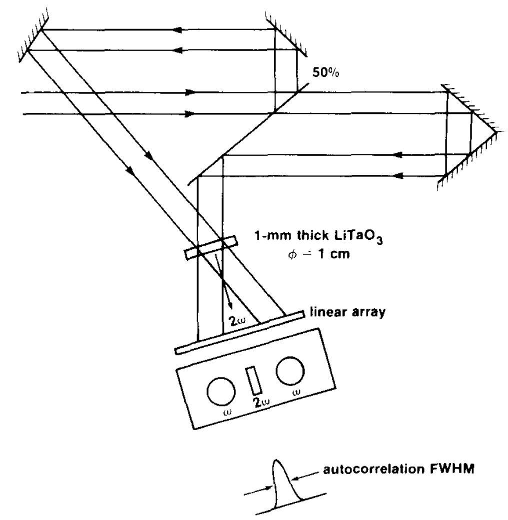

Fig. 5. Single-shot autocorrelator.

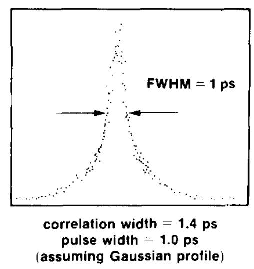

Fig. 6. Autocorrelation trace of the 500 mJ pulse showing a pulsewidth of 1 ps assuming a Gaussian profile.

III. Towards 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/compressed pulse duration $= r$. Single-stage compression of CW mode-locked YAG or YLF limits the value of r to approximately 300. This limitation stems from the nonlinear relationship of 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 [15]

$$\begin{aligned}\tau(\lambda_0 + \Delta\lambda) &= \tau_0 + 2\frac{\lambda_0}{c} L \frac{m^2}{a^2 \cos^3 \theta} \Delta\lambda \\ &\quad + \frac{3Lm^2}{ca^2 \cos^3 \theta}\left(1 + \frac{\lambda_0 m \sin \theta}{a \cos^2 \theta}\right)(\Delta\lambda)^2 \\ &= \tau_0 + \tau_1 + \tau_2\end{aligned}$$

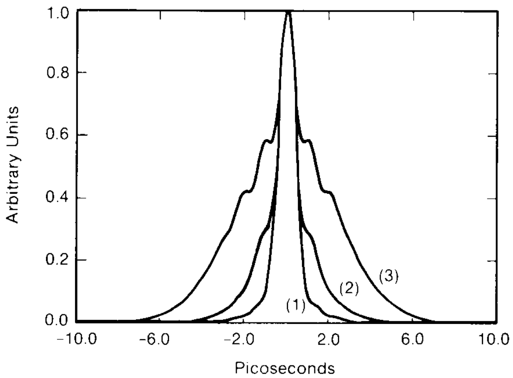

Fig. 7. Autocorrelation of compressed pulses for a 35 Å spectrum: (1) without quadratic delay, (2) with quadratic delay for a 300 ps chirped pulse, (3) with quadratic delay for a 600 ps chirped pulse.

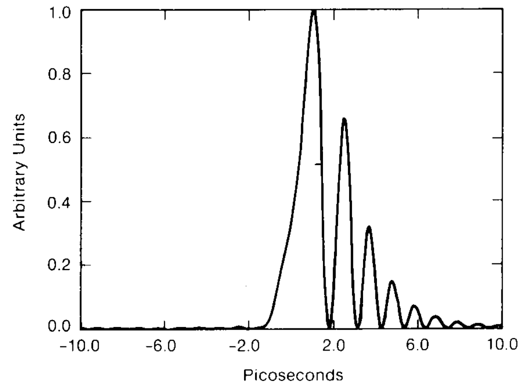

Fig. 8. Temporal profile resulting of the compression of a 600 ps chirped pulse.

where $\lambda = \lambda_0 + \Delta\lambda$ is the wavelength, λ_0 is the central wavelength of the pulse, c is the speed of light, L is the distance between the planes containing the gratings, m is the diffraction order, a is the line spacing, and θ is 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. Fig. 7 demonstrates the effect of τ_2 as the chirped pulse duration increases, while keeping the bandwidth constant. The grating spacing has been chosen to cancel τ_1. The autocorrelation function is seen to have increased sidelobes, while its 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. 8). Measurements done with a CW mode-locked Nd:YAG coupled in 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. 9). Using a 0.8 nm interference filter, leaving all other parameters identical, results in a very clean 2 ps pulse (Fig. 10).

Both simulation and experiments clearly show the limitation of fiber-grating compression for the CPA technique due to 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 [16]. This solution is not applicable here: prisms are not dispersive enough to yield reasonable physical dimensions in the picosecond domain.

Martinez [17], [18] has described an arrangement which uses a telescope between a grating pair in order to provide a net positive GVD. This offers the possibility of both stretching and compressing the pulses with dispersive devices that are perfectly matched to one another. We have recently demonstrated the validity of this technique by stretching a pulse more than 1000 times and then recompressing it back to within 10 percent of its original pulsewidth by using gratings in both positive and negative GVD modes [19].

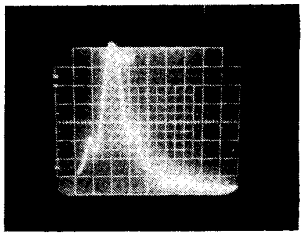

Fig. 9. Autocorrelation trace of a 40 Å bandwidth compressed pulse.

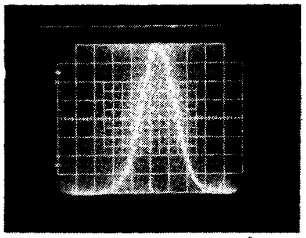

Fig. 10. Autocorrelation trace of a filtered 8 Å bandwidth compressed pulse.

The experiment was done using a synchronously pumped, colliding-pulse mode-locked dye laser. The dye laser delivered 80 fs pulses with a bandwidth of 4.8 nm (FWHM) centered at 617 nm. The experimental arrangement for both stretching and recompressing the pulse is shown in Fig. 11. The pulse stretcher consists of two 1700 l/mm gratings separated by 130 cm in an anti-parallel configuration lying within the focal planes of a unit magnification telescope. This arrangement provides a net positive GVD. Double passing the pulse through the system yields an output 85 ps in duration. Two identical gratings in a standard parallel configuration are then used to compress the pulse back to 90 fs (see Fig. 12). This clearly

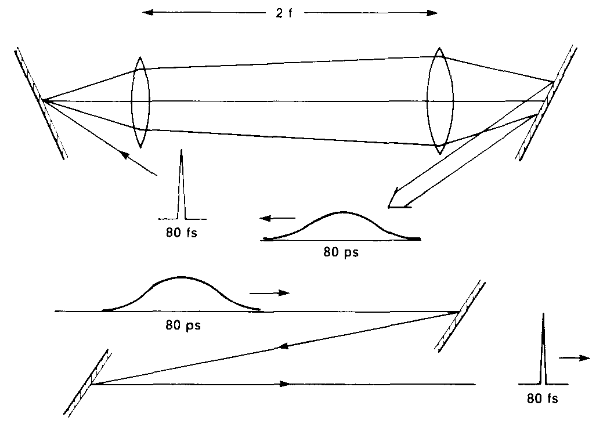

Fig. 11. Expansion–compression setup.

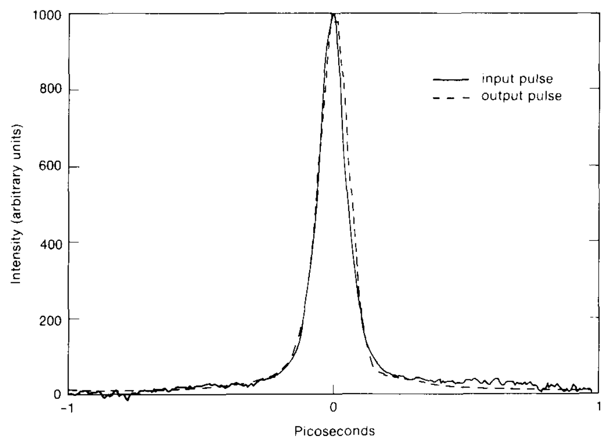

Fig. 12. Comparison of the autocorrelation traces of the input and output pulses from the expansion–compression stage.

demonstrates that the stretcher and compressor are perfectly matched.

By using this technique, we are now able to completely decouple the duration of the short compressed pulse from the duration of the long chirped pulse. This now makes it feasible to consider compression of the YLF oscillator to generate 500 fs pulses. Subsequent expansion to 1 ns prior to amplification to 3–4 J followed by compression will lead to pulses of ~6 TW peak power with our current amplification system. Our current limitation being the damage threshold of the gold coating used for the gratings, we are investigating other types of gratings. Transmission gratings written in dichromated gelatines, for example, have already shown a damage resistance ten times higher than gold-coated gratings.

In conclusion, chirped pulse amplification has been used to produce single picosecond pulse to the terawatt level. The beam divergence is 2.2 times the diffraction limit, making the brightness of this source greater than 10^{+18} $W/(cm^2 \cdot sr)$, 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. This means that with the present amplifier, energies on the order of 3–4 J can be reached after stretching to 1 ns, thus leading to a peak power of a few terawatts. Although it seems that gain narrowing limits this technique to the amplification of about 500 fs pulses in Nd:glass, shorter pulses could be obtained by artificially broadening the overall amplifier bandwidth using different types of glass. Even more exciting is the fact that the CPA technique can be used with very large Nd:glass amplifiers such as the Glass Development Laser at Rochester. From this system, a near 1 kJ energy level can be extracted with 1 ns pulse. These pulses can then be recompressed to the subpicosecond level producing pulses, well in the petawatt regime, that when focused over a few times diffraction-limited spot would allow power densities in the range of 10^{23} W/cm^2.

Acknowledgment

We thank the Laboratoire d'Optique Appliquée, E.N.S.T.A., Palaiseau, France, for the loan of the 16 mm amplifier, and Lawrence Livermore National Laboratory for the loan of the diffraction gratings. We also thank Corning for generously providing us with the single-mode fiber.

References

[1] W. Koechner, *Solid-State Laser Engineering*. New York: Springer-Verlag, 1976, p. 581.

[2] A. P. Schwarzenbach, T. S. Luk, I. A. McIntyre, U. Johann, A. McPherson, K. Boyer and C. K. Rhodes, "Subpicosecond KrF* excimer-laser source," *Opt. Lett.*, vol. 11, pp. 499–501, 1986.

[3] L. G. Deshazer, "Advances in tunable solid-state lasers," *Laser Focus*, vol. 23, no. 5, pp. 54–58, 1987.

[4] T. Damm, T. Kaschke, F. Noack, and B. Wilhelmi, "Compression of picosecond pulses from a solid-state laser using self-phase modulation-graded index fibers," *Opt. Lett.*, vol. 10, no. 4, 1985.

[5] D. Strickland and G. Mourou, "Compression of amplified chirped optical pulses," *Opt. Commun.*, vol. 56, pp. 219–221, 1985.

[6] D. Strickland, P. Maine, M. Bouvier, S. Williamson, and G. Mourou, "Picosecond pulse amplification using pulse compression techniques," in *Ultrafast Phenomena V*, G. R. Fleming and A.E. Sigman, Eds. New York: Springer-Verlag, 1986, pp. 38–42.

[7] P. Bado, M. Bouvier, and J. S. Coe, "Nd:YLF mode-locked oscillator and regenerative amplifier," *Opt. Lett.*, vol. 12, pp. 319–321, 1987.

[8] S. Szatmari, F. P. Schäfer, E. Müller-Horsche, and W. Mückenheim, "Hybrid dye-excimer laser system for the generation of 80 fs, 900 GW pulses at 248 nm," presented at CLEO 1987, Baltimore, MD.

[9] H. Nakatsuka and D. Grischkowsky, "Recompression of optical pulses broadened by passage through optical fibers," *Opt. Lett.*, vol. 6, pp. 13–15, 1981.

[10] H. Roskos, A. Seilmeier, W. Kaiser, and J. D. Harvey, "Efficient high power optical pulse and precision with logarithmic wing analysis," *Opt. Commun.*, vol. 61, no. 1, 1987.

[11] J. Desbois, F. Gires, and P. Tournois, "A new approach to picosecond laser pulse analysis shaping and coding," *IEEE J. Quantum Electron.*, vol. QE-9, pp. 213–218, 1973.

[12] B. H. Kolner, D. M. Blomm, J. D. Kafka, and T. M. Baer, "Compression of mode-locked Nd:YAG pulses to 1.8 ps," in *Ultrafast Phenomena IV*, pp. 19–22.

[13] E. E. Martinez, "Grating and prism compressor in the case of finite beam size," *J. Opt. Soc. Amer.*, vol. 3, no. 7, 1986.
[14] J. Janszky, G. Corradi, and R. N. Gyuzalian, "On a possibility of analyzing the temporal characteristics of short light pulses," *Opt. Commun.*, vol. 23, pp. 293–298, 1977.
[15] J. D. McMullen, "Analysis of compression of frequency chirped optical pulses by a strongly dispersive grating pair," *Appl. Opt.*, vol. 18, pp. 737–741, 1979.
[16] C. H. Brito-Cruz, R. L. Fork, and C. V. Shank, "Compression of optical pulses to 6 fs using cubic phase distortion compensation," presented at CLEO 1987, Baltimore, MD, paper MD1.
[17] O. E. Martinez, J. P. Gordon, and R. L. Fork, "Negative group-velocity dispersion using refraction," *J. Opt. Soc. Amer. A*, vol. 1, pp. 1003–1006, 1984.
[18] O. E. Martinez, "3000 times grating compressor with positive group velocity dispersion: Application to fiber compensation in 1.3, 1.6 μm regime," *IEEE J. Quantum Electron.*, vol. QE-23, pp. 59–64, Jan. 1987.
[19] M. Pessot, P. Maine, and G. Mourou, "1000 times expansion/compression of optical pulses for chirped pulse amplification," *Opt. Commun.*, vol. 62, no. 6, pp. 419–421, 1987.
[20] F. Salin, P. Georges, G. Roger, and A. Bron, "Single shot measurement of 52 femtosecond pulses," *Appl. Opt.*, vol. 26, Nov. 1987.

P. Maine, photograph and biography not available at the time of publication.

D. Strickland, photograph and biography not available at the time of publication.

P. Bado, photograph and biography not available at the time of publication.

M. Pessot, photograph and biography not available at the time of publication.

G. Mourou, photograph and biography not available at the time of publication.