8. W. D. Kingery *et al., Introduction to Ceramics* (Wiley, New York, 1975), p. 110.
9. Analysis performed by Xerox Analytical Laboratory, Jos. C. Wilson Center for Technology, Webster, NY.
10. Dr. W. LaCourse, Institute for Glass Science and Engineering, Alfred University, Alfred, NY (private communication).

3.B Short-Pulse Amplification Using Pulse-Compression Techniques

Traditionally, short pulses have been amplified by dye or excimer amplifers. Nd:glass, in spite of its remarkable energy-storage capability, was not utilized because of the difficulty to extract efficiently the stored energy at a high repetition rate. A technique analogous to the one used in the radar field is described, which allows the amplification of short pulses to a level two to three orders of magnitude beyond the state of the art. This technique should make possible the generation of picosecond pulses at the joule level.

As early as 1940, scientists[1-5] working in radar proposed to amplify short pulses, using compression techniques as a way to decrease the peak power in the transmitter tubes while increasing the radar range and resolution. The general approach is shown in Fig. 25.29(a). It uses a linearly chirped pulse with a total frequency modulation ΔF. The pulse, after traversing some dispersive elements, is stretched to a length several times its original value so it can be amplified efficiently without reaching a prohibitive peak power. After amplification, the pulse is broadcast. Its echo is compressed by a matched filter to a pulse width approximately equal to $1/\Delta F$. The final result is a large increase in both radar range and accuracy.

In the laser field, scientists and engineers working in short-pulse amplification have faced the same peak-power limitation in laser amplifier stages.[6] Pulses in the picosecond range can quickly reach relatively high peak intensities in the GW/cm^2 range. At these intensities, nonlinear effects occur that may cause beam wave-front distortion, filamentation, and irreversible damage to components. The net result is that short-pulse amplifiers have to be operated in a small-signal-gain regime far from saturation, leading to unwieldy, inefficient systems working at low repetition rate. Nd:glass amplifiers are a good example. In the absence of nonlinear effects, Nd:glass is capable of amplifying optical pulses up to a fluence of 5 J/cm^2 before saturation occurs, as opposed to 3 mJ/cm^2 for dye amplifiers. For a 1-ps pulse, 5 J/cm^2 corresponds to a power density of 5 TW/cm^2, about one thousand times the limit set by nonlinear effects in glass. This constraint can now be overcome by a technique analogous to short-pulse amplification in radar.

The principle of the amplification is depicted in Fig. 25.29(b). Relatively short, low-energy pulses are delivered by a mode-locked oscillator. Before amplification, they are coupled into a single-mode fiber, where they simultaneously experience self-phase modulation and group velocity dispersion. The self-phase modulation taking place at the early part of the fiber produces sidebands to the laser spectrum, whereas the group velocity dispersion stretches each pulse into a rectangular pulse with a duration several times its initial value.

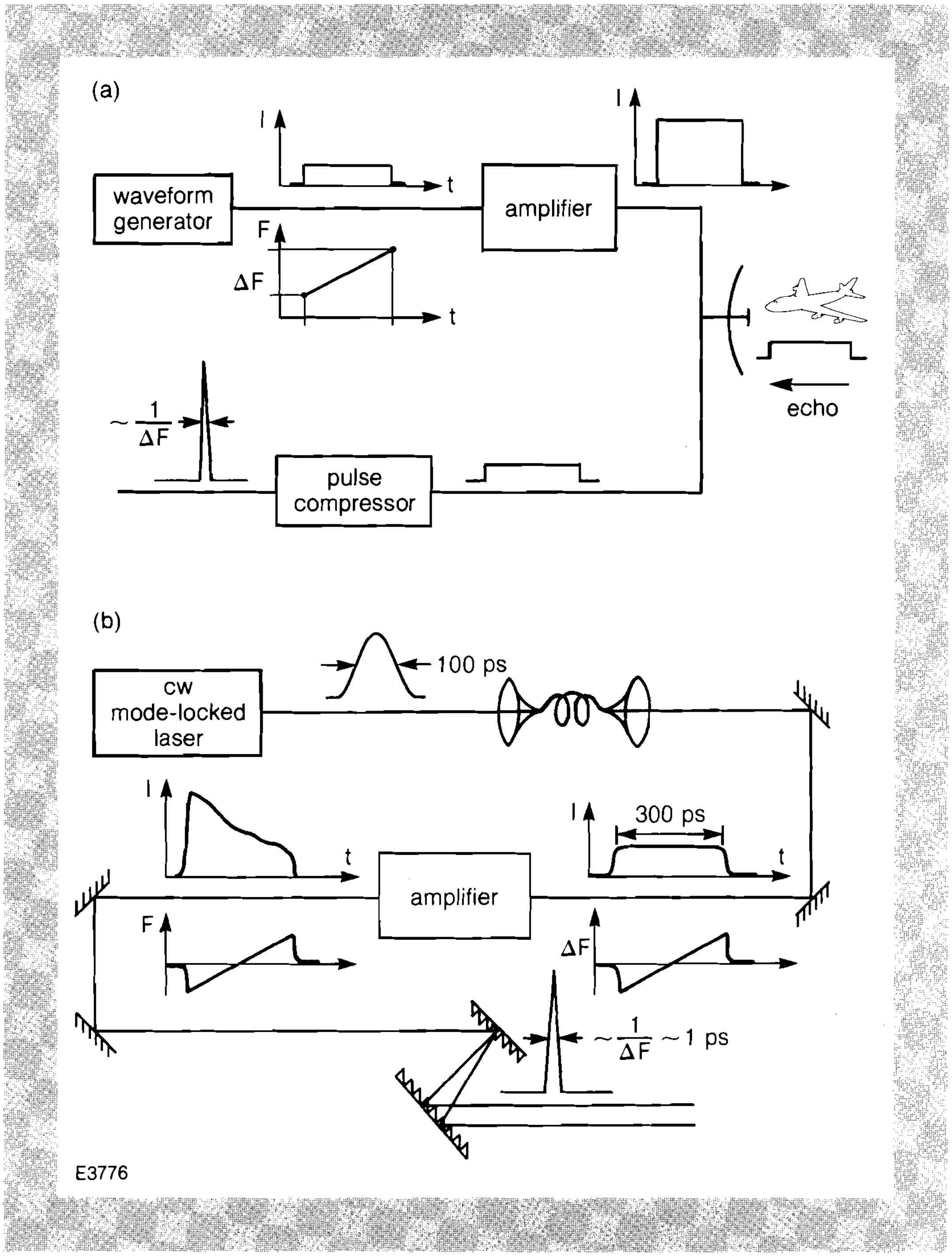

Fig. 25.29
The pulse compression of chirped pulse in radar (top) and its optical analog.

At the fiber output the pulses have a rectangular pulse envelope with a linearly swept carrier frequency.[7] At this point the coded pulses are amplified without fear of undesirable nonlinear effects. The amplifier gain bandwidth has to be broader than the pulse spectrum in order not to limit the pulse spectrum. After amplification, the pulse is compressed in time by a pair of gratings to a value approximately equal to $1/\Delta F$ of the initial value. This short-pulse amplification scheme, using frequency chirping and pulse compression, has recently been demonstrated.[8]

A cw mode-locked Nd:YAG laser is used to produce low-energy, 100-ps optical pulses at a 100-MHz repetition rate. The pulses are injected into a 1.4-km-long single-mode fiber. Due to the combined effect of self-phase modulation and group velocity dispersion, pulses of 200 ps exhibiting a linear chirp are produced at the fiber output (see Fig. 25.30). The linear chirp is spread over 40 Å. The 200-ps pulses are injected into a regenerative amplifier using silicate glass (Kigre Q-246) as the active medium, which exhibits a gain bandwidth of 200 Å. The pulses are injected into the regenerative-amplifier cavity at a repetition rate of 5 Hz by a single Pockels cell. After 40 round trips in the laser cavity, the laser pulses attain an energy of 2 mJ and are cavity dumped by the same Pockels cell. Because of gain saturation the output-pulse amplitude is not rectangular but still exhibits a linear frequency chirp across the pulse. The pulse is subsequently compressed by a set of two gratings to a pulse width of 1.5 ps. The overall grating efficiency is 50%, yielding an output pulse of 1 mJ. Figure 25.31 shows a streak camera trace of the amplified and compressed pulse and a reflection from an etalon.

If we compare this system to other existing systems[9] based on dye lasers amplified by Nd:YAG or excimer lasers, producing millijoule-level pulses of 1 ps at a similar repetition rate, one is struck by the simplicity, compactness, beam quality, and much superior efficiency

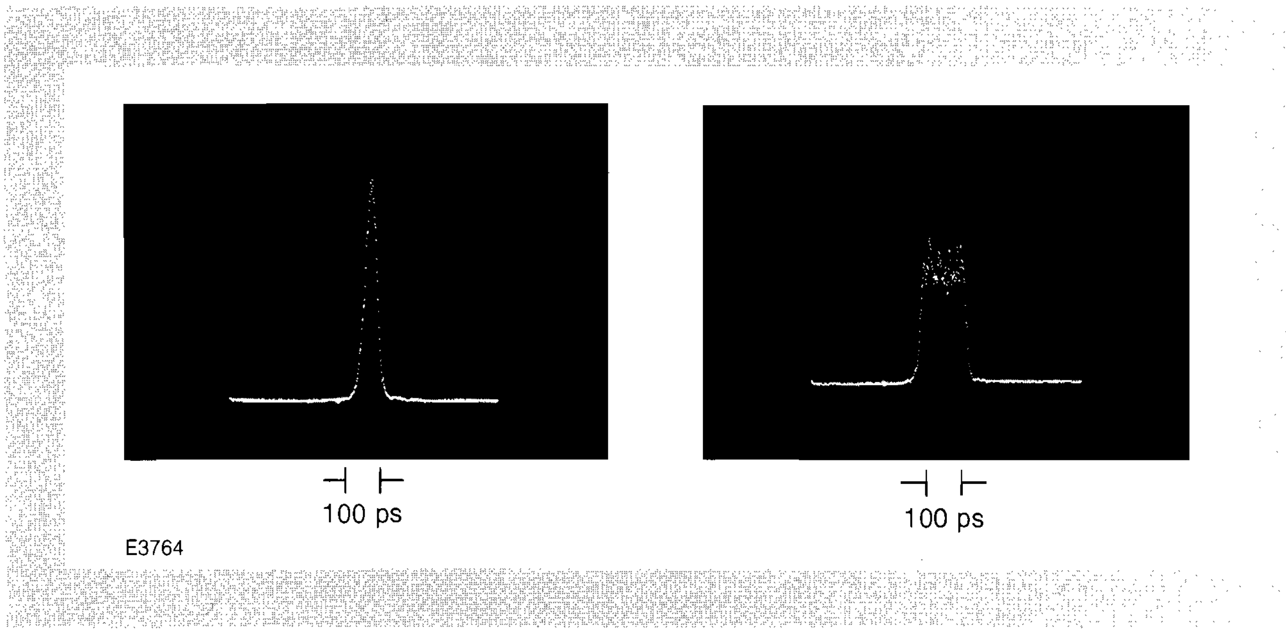

Fig. 25.30
Pulses at the fiber input and output monitored by a streak camera. The pulse has been frequency doubled for detection needs.

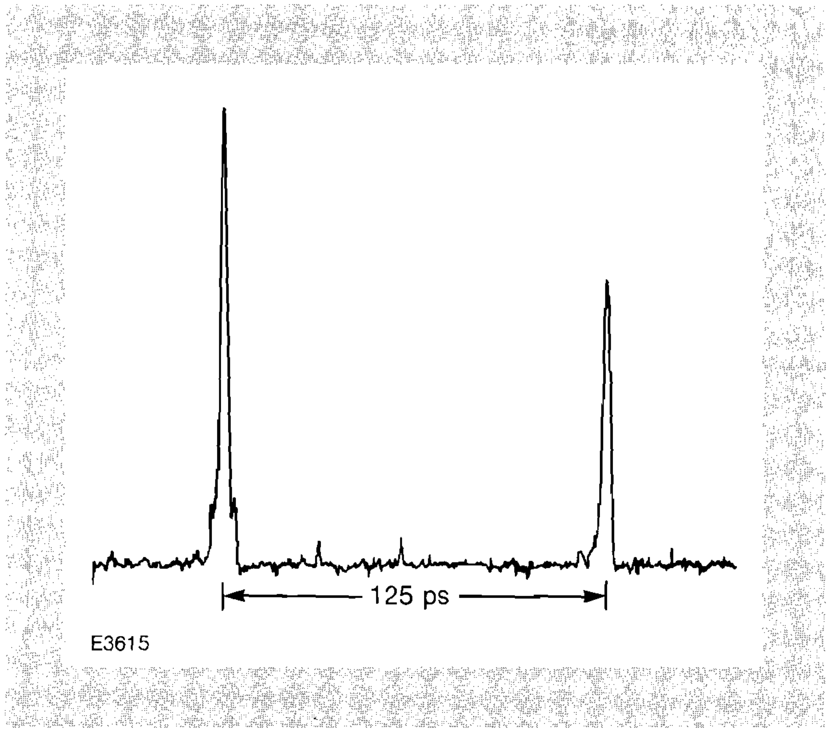

Fig. 25.31
Short pulses after amplification. Because the streak camera has a visible photocathode, the pulse had to be frequency doubled.

of this system. It is worth noting the enormous potential of this concept especially for glass systems – which, unlike dyes, have a large energy-storage capability. Pulses with durations of a few hundred picoseconds are presently amplified from the joule to the kilojoule level, and now, with this technique, femtosecond and picosecond pulses with equivalent energies may be produced. Opportunities arise for sources two to three orders of magnitude brighter than existing ones; conversely, one could produce equivalent brightness with a system that had 10^2 to 10^3 times less energy per pulse. To illustrate the dramatic improvement this technology offers, Fig. 25.32 shows the experimental curve of the energy per pulse as a function of pulse width available on the glass development laser at LLE. We have also plotted the energy available with the pulse compression technique. Curve (a) represents what could be obtained today and curve (b), what could be obtained assuming that nanosecond-to-picosecond compression is possible. The curves (a) and (b) are, of course, parallel to the time axis because the pulse is amplified at constant pulse width. It is the compression that determines the pulse duration.

We have demonstrated that a technique of pulse chirping is able to produce pulses with a brightness two to three orders of magnitude greater than any existing source. Pulses with peak powers of 10^{15} to 10^{16} W can in principle be achieved, opening new possibilities for studying matter under intense irradiation.[10] For the spectroscopist interested in the picosecond time scale, this new system is simpler, more efficient, more compact, less costly, and has sufficient power density to produce white-light continua. Finally, this system makes long-range and high-accuracy radar possible because of the large amount of energy now available in short pulses.

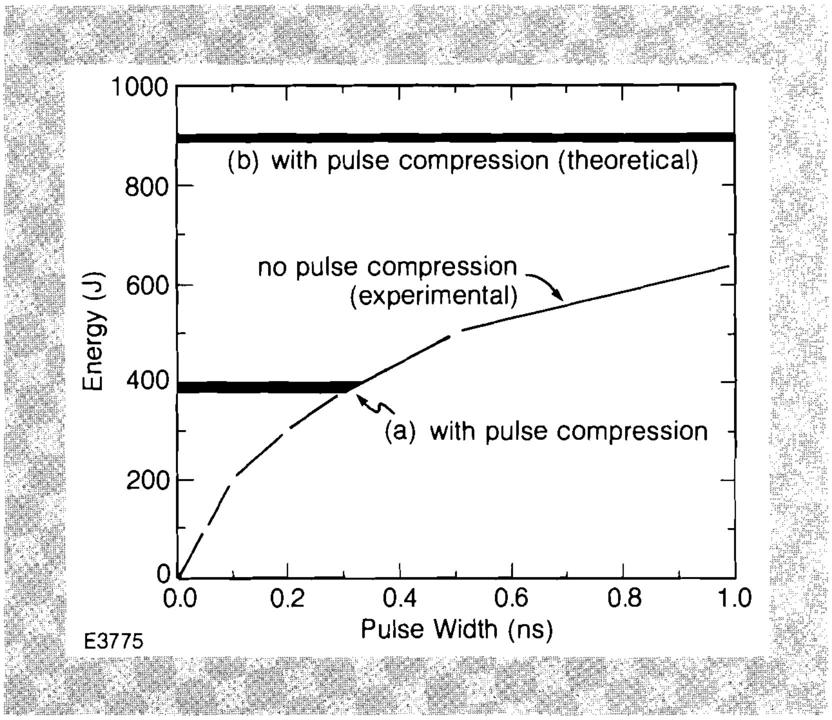

Fig 25.32
Energy obtainable on the glass development laser at LLE as a function of the laser pulsewidth. Note that for the curves (a) and (b), the energy is independent of the final laser pulsewidth since the amplifier sees a constant input pulsewidth.

ACKNOWLEDGMENT

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REFERENCES

1. E. Huttman, German Patent No. 768068 (22 March 1940).
2. W. A. Cauer, German Patent No. 892772 (19 December 1950).
3. D. O. Sproule and H. J. Higle. British Patent No. 604429 (5 July 1948).
4. R. H. Dicke. U.S. Patent No. 2 624 876 (6 January 1953).
5. S. Darlington. U.S. Patent No. 2 678 997 (18 May 1954).
6. For instance see M. M. T. Loy and Y. R. Shen, *IEEE J. Quantum Electron* **9**, 409 (1973) or W. Koechner, *Solid State Laser Engineering* (Springer-Verlag, 1976), p. 592.
7. H. Nakatsuka and D. Grischkowsky, *Opt. Lett.* **6**, 13 (1981).
8. D. Strickland and G. Mourou, *Opt. Commun.* (to be published).
9. For a review of various amplification schemes, see *Picosecond Phenomena III: Proceedings of the Third International Conference on Picosecond Phenomena (1982),* edited by K. B. Eisenthal, R. M. Hochstrasser, W. Kaiser, and A. Laubereau (Springer-Verlag, 1982), pp. 10, 19, and 107.
10. K. Boyer and C. K. Rhodes, *Phys. Rev. Lett.* **54**, 1490 (1985).