Compression of picosecond pulses from a solid-state laser using self-phase modulation in graded-index fibers

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We report the compression by a factor of 7 of 2-μJ pulses of 5-psec duration from a mode-locked Nd:phosphate glass laser. The pulses were chirped and their spectrum broadened while traveling through a graded-index core fiber. After amplification to 500 μJ, they were finally compressed by traveling through a dispersive delay line, and 0.7-psec pulse widths were achieved.

Short light pulses of high power are needed for many investigations of fast physical, chemical, and biological phenomena by time-resolved spectroscopy. One important method for shortening light pulses utilizes the frequency sweep produced by self-phase modulation in a nonlinear medium, in which the pulse is spectrally broadened. After leaving the nonlinear medium the pulses can be compressed to the bandwidth limit by traveling through a linear medium (e.g., a delay line) that exhibits the appropriate group-velocity dispersion.[1,2] Optical fibers with low loss are favored as the nonlinear medium because they exhibit strong nonlinear effects owing to their small core diameters and long path lengths. This compression method has been demonstrated in a number of experiments using picosecond and femtosecond cw dye lasers, single-mode fibers, and grating pairs.[3–5] Pulses from a cw Nd:YAG laser have also been compressed by this technique.[6]

In previous pulse-compression experiments, the pulse energy was restricted to rather small values because of the small core diameter of typical single-mode fibers. Here we address the question of whether this method of pulse compression is feasible with picosecond pulses of higher energy, such as those from pulsed solid-state lasers. It should be mentioned that mode-locked solid-state oscillators generate pulses with energies much higher than those of cw oscillators. Although high pulse energy is desirable, damage in the nonlinear medium may become a serious problem.

In this Letter we report the compression of 5-psec pulses from a pulsed Nd:phosphate glass laser by a factor of 7 to pulses with a duration of 0.7 psec (FWHM) and an energy of 0.5 mJ. Our experimental setup is shown in Fig. 1. A single pulse (typical FWHM, 5 psec; pulse energy, 30 μJ; wavelength, 1054 nm) is selected from the pulse train emitted by a Nd:phosphate glass laser. The 5-cm^{-1} pulse bandwidth justifies the assumption of a nearly bandwidth-limited pulse [Figs. 2(a) and 3(a)]. All pulse-duration measurements were made using the two-photon fluorescence (TPF) technique in Rhodamine 6G,[7] and spectra were recorded using a Jobin Yvon H 25 grating spectrometer. To avoid damage to the fiber, the single pulse was attenuated by a factor of 15 to 2 μJ before being coupled into the 40-cm-long graded-index core fiber using a microscope objective (f = 35 mm). We used graded-index fibers (GIF's) instead of single-mode fibers (SMF's) because the GIF combines small mode dispersion with a comparatively large core diameter. The 50-μm-core GIF can accept 1 to 2 orders of magnitude higher pulse energies than can a SMF (5-μm core) before reaching the damage threshold.

Pulses propagating through a long fiber will experience temporal broadening owing to group-velocity dispersion (GVD), which in general is not desired. However, it has been shown that the effect of GVD can be used to obtain better-compressed pulse shapes.[8–10] We neglect the influence of GVD[11] since our fiber was comparatively short and the laser wavelength was close to the zero-dispersion wavelength, which is about 1.3 μm for silica fibers.

The following wave equation applies when both GVD and losses are neglected[12]:

$$i\frac{\partial}{\partial\zeta}E(\zeta,\eta)-\kappa|E(\zeta,\eta)|^2E(\zeta,\eta)=0, \qquad (1)$$

where $\eta = t - z/v$ and $\zeta = z$ are the local coordinates and

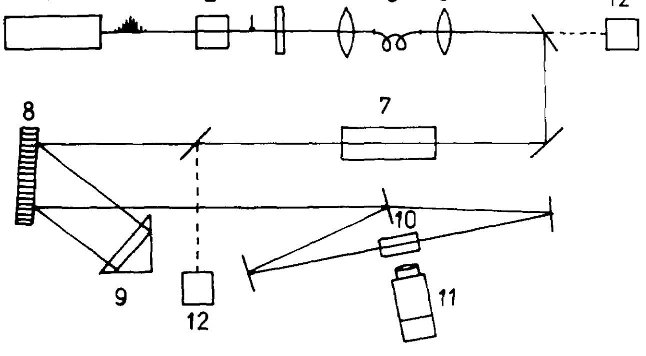

Fig. 1. Experimental setup: 1, Nd:phosphate glass laser; 2, single pulse selection; 3, neutral filter; 4, 6, micro objectives; 5, graded-index core fiber; 7, amplifier; 8, grating; 9, prism; 10, TPF setup; 11, OMA2 vidicon; 12, spectrograph.

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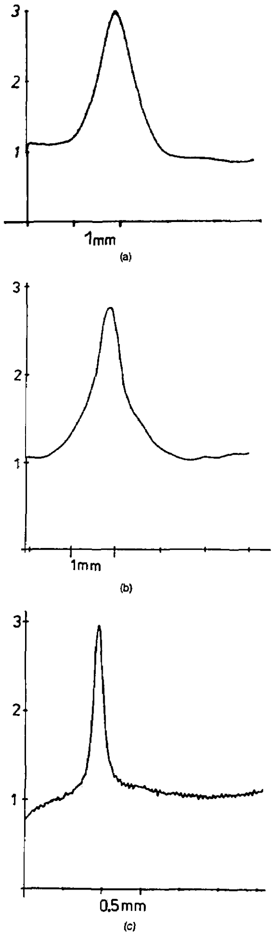

Fig. 2. (a) TPF trace of laser pulse. (b) TPF trace of amplified chirped pulse. (c) TPF trace of compressed pulse.

κ is related to the nonlinear refractive index by $\kappa = 0.5k_0\, n_2/n_0$, where $n(t) = n_0 + n_2E(t)^2$. The solution of Eq. (1) is

$$E(\zeta, \eta) = E(0, \eta) \exp[-i\kappa|E(0, \eta)|^2\zeta], \qquad (2)$$

which for $n_2 > 0$ results in an upchirped pulse of unchanged duration whose instantaneous frequency is a nearly linear function of time about the pulse center. The broadened spectrum of the self-phase-modulated pulse is shown in Fig. 3. The chirped pulse was then amplified. A bandwidth-limited pulse will always be broadened in time by passage through an optical element with a finite bandwidth (e.g., a filter, an amplifier), whereas a chirped pulse can be shortened, as has been demonstrated by Ippen and Shank.[13] Because of the high amplification necessary to compensate for losses and to provide suitable energies for TPF measurements, the effective bandwidth of the amplifier (about 5 nm) leads to a slightly shortened pulse, as shown in Figs. 2(b) and 4 at $L_D = 0$. It should be noted, however, that the finite amplifier bandwidth limits the usable fiber length. A long fiber leads to a pulse spectrum much broader than the amplifier bandwidth, so that only a fraction of the pulse energy will be amplified. Raman-scattering losses in longer fibers is another limitation. In our 40-cm fibers no Raman signals were detected, but when the fiber length was increased 20 times, strong Raman signals down to $\lambda = 0.8$ μm were observed.[11]

The amplified pulse was compressed in a dispersive delay line consisting of a 651-line/mm holographic grating and a right-angle prism.[14] The grating blaze wavelength was 1020 nm, the angle of incidence was 2°, and the first-order diffraction angle was 40°. The transmission of the grating-prism delay line was 45%. The delay length L_D could be varied between 12.5 and 95 cm. Increased pulse widths were observed for delay-line lengths both longer and shorter than optimum (Fig. 4).

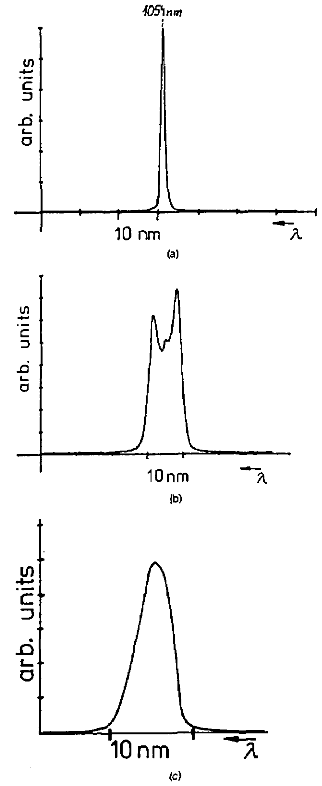

Fig. 3. (a) Spectrum of laser pulse. (b) Spectrum of chirped pulse. (c) Spectrum of amplified chirped pulse.

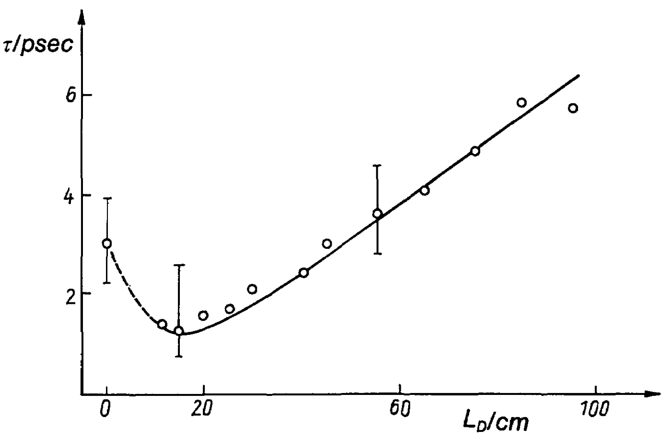

Fig. 4. Duration of compressed pulses versus delay length.

A typical TPF trace of a compressed pulse is shown in Fig. 2(c); it has a length of 0.14 mm, measured by imaging onto the optical multichannel analyzer vidicon. The spatial resolution of this system was measured to be 0.1 mm from the image of a keen wedge. Considering the spatial resolution and the refractive index of the solution of Rh 6G in ethylene glycol ($n = 1.435$), a Gaussian-shaped pulse corresponding to the TPF trace would have a duration of 0.7 psec.

In summary, we have experimentally demonstrated pulse compression using graded-index fibers and have produced subpicosecond pulses with energies in the microjoule range.

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