Generation of 33-fsec pulses at 1.32 μm through a high-order soliton effect in a single-mode optical fiber

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Pulse shortening by a factor of 2700X at 1.32 μm has been realized by means of a two-stage pulse compression. In the first stage, 90-psec pulses from a cw mode-locked Nd:YAG laser were compressed to ~1.5 psec by using a standard fiber-grating-pair configuration. Subsequent propagation of these pulses through ~20 m of single-mode optical fiber with a minimum dispersion at 1.27 μm led to a final pulse width of 33 fsec. This represents the shortest reported pulse generated at 1.32 μm by using the technique described above as well as the largest overall compression factor using optical fibers yet reported.

Optical pulse compression in the region of positive group-velocity dispersion in optical fibers, generally below 1.3 μm, requires an additional negatively dispersive delay line in order to compensate for the generated positive chirp in the fiber. Most commonly, this is supplied by a diffraction grating assembly, although other arrangements are possible. By using fiber-grating pairs, generated pulses at 620 nm as short as 8 fsec have been measured by a collinear autocorrelation technique. At wavelengths above the dispersion minimum, Hasegawa and Tappert have theoretically shown that the intensity-dependent nonlinearity of the refractive index can compensate for the broadening due to group-velocity dispersion. In a lossless regime and neglecting the effects of higher than second-order dispersion, they have shown that the solution of the nonlinear Schrödinger equation describing the system gives rise to the special class of pulselike solutions, the now familiar solitons. In fibers, solitons were first observed by Mollenauer et al., and their importance in future optical communications has been discussed by several authors.

The technological advance in fiber fabrication has allowed some degree of flexibility with respect to the location of the zero-dispersion wavelength. This has permitted a new method for pulse compression to be achieved, for example, through an all-fiber compressor, as was demonstrated by Blow et al.

An alternative approach was recently demonstrated by Tai and Tomita in which the 100-psec pulses from a mode-locked Nd:YAG laser operating at 1.319 μm were first compressed to 2 psec by using a fiber-grating compressor (the fiber having a minimum dispersion wavelength at 1.5 μm). The compressed pulses were subsequently propagated through 40 m of fiber with λ0 = 1.27 μm (thus the fiber was negatively dispersive) to generate pulses, through high-order soliton effects, with 90-fsec duration.

In this Letter, using a scheme similar to that of Ref. 14, we report our study of higher-order soliton propagation and generation of pulses as short as 33 fsec, which corresponds to an overall compression ratio of 2727X. These results demonstrate, to our knowledge, the shortest pulse generated at this wavelength as well as the largest compression factor achieved using optical fibers.

The experimental scheme is similar to that described in Ref. 14. The first-stage compressor was composed of 200 m of dispersion-shifted (λ0 = 1.5 μm) optical fiber followed by a pair of diffraction gratings (1200 lines/mm) separated by an optical path of 1.7 m in a double-pass arrangement. The initially 90-psec-duration, 1.5-W average-power pulses from the cw mode-locked Nd:YAG laser operating at 1.32 μm were reduced by a factor of 60 to durations of ~1.5 psec with average powers of 370 mW (2.2-kW peak power). These pulses were then coupled into 19.5 m of single-mode fiber, with zero dispersion at 1.275 μm, an effective core area of 96 μm^2, and a dispersion value D = -5 psec/nm km at 1.32 μm. The loss was <0.5 dB/km at 1.32 μm. The power into this second fiber was varied by axially translating the input focusing microscope objective (20X, uncoated).

Typically 100 mW of average power was obtained at the output end of the second fiber. This corresponds to 587-W peak power (for a pulse width of 1.5 psec at a repetition rate of 100 MHz). Theory predicts that the soliton period will be 246 m (using our fiber parameters) and the fundamental soliton power P0 will be 4.16 W. For peak powers up to 587 W, a soliton number of N ≈ 11.8 is predicted. Given an N = 12 soliton, the calculated first optimal narrowing, according to Ref. 7, is τ/τ0 ≈ 0.02 (50X compression), where τ0 is the initial pulse width. For N = 8 and N = 11, compression factors of approximately 30 and 40, respectively, are predicted.

The results shown in Figs. 1(a)–1(c) are the second-order autocorrelation recordings of the pulses propagated through 19.5 m of fiber (Z/τ0 = 0.079) for peak powers of 293, 469, and 587 W corresponding to N = 8, 11, and 12, respectively. The autocorrelation measurements in this figure were obtained by the collinear beams method.

Figure 2 shows autocorrelations obtained at similar power levels to those in Fig. 1 but using the background-free method. The identical nature of the au-
The behavior with further decreases in the fiber length. The autocorrelations corresponding to the fiber-length decrease from optimum exhibited the narrow spike embedded on a broad pedestal of increasing intensity until the pulse width amounted to hundreds of femtoseconds. A more detailed study of this sequence will be reported elsewhere. With increased fiber length, as great as 200 m, the autocorrelation showed a slowly temporally broadening pulse with a maximum width of ~200 fsec at 200 m. This would indicate that a single soliton formed in the initial 20 m was slowly broadening on propagation through the low-loss fiber.

The change in the soliton pulse behavior when the fiber length was decreased from \( Z/Z_0 = 0.079 \) to \( Z/Z_0 = 0.04 \) can be seen through the changes in the corresponding spectra, shown in Figs. 4(a) and 4(b), respectively. These spectra were recorded on a 1-m spectrograph with a spectral resolution of 0.2 nm. For \( Z/Z_0 = 0.079 \), the optimum compression, giving the 33-fsec pulse, a broad self-phase-modulated-type spectrum with symmetrical sidelobes is in evidence, with an

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**Fig. 1.** Autocorrelation traces of pulses generated through soliton propagation in 19.5 m of single-mode optical fiber for powers of (a) 293 W \((N = 8)\), (b) 469 W \((N = 11)\), and (c) 587 W \((N = 12)\).

**Fig. 2.** Autocorrelation traces corresponding to Fig. 1, recorded using background-free technique to show the nonsoliton component of the compressed pulse; fs, femtoseconds.
asymmetry in intensity to the long wavelength. With the reduced fiber length, $Z/Z_0 = 0.04$ [Fig. 4(b)], the self-phase modulation is present but the sidelobes and the spectral extent were substantially reduced.

The experimentally determined optimum fiber length disagreed substantially with the theoretically predicted value, the former being greater by a factor of ~2.5. However, the input pulses to the second fiber are not quite transform limited.\cite{15} In addition, near the minimum dispersion, Wai et al.\cite{17} have shown that the third-order term affects the results of soliton propagation in the low orders and should also be important for higher orders.

It was recently shown theoretically\cite{18} that nonlinearities can cause instability in the slow mode of solitons propagating in a birefringent fiber. In this condition high-order solitons break up, with a significant fraction of the pulse energy being transferred into a single soliton exhibiting a large compression ratio. It is possible that this phenomenon may be playing a role in our results. Although our fiber was not birefringent, defects and strain-induced birefringence could lead to the generation of two linearly polarized components, and it is possible that this or a related process could be contributing to the soliton-formation process. We are at present investigating the polarization nature of the generated solitons.

In conclusion, we have reported on the generation of pulses of 33-fsec duration at 1.32 μm through high-order ($N = 12$) soliton effects, which occurs rapidly with length in dispersion-shifted ($\lambda_0 = 1.27 \mu m$) optical fiber. These pulses have an estimated peak power of $1.5 \times 10^4$ W, are the shortest pulses generated at this wavelength yet reported to our knowledge, and represent an overall pulse compression of approximately 2700 times from the cw mode-locked Nd:YAG laser pulses from which they are derived.

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References