Soliton pulse compression in dispersion-decreasing fiber

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We investigate the adiabatic compression of picosecond and subpicosecond soliton pulses from all-fiber, passively mode-locked, erbium-doped fiber soliton lasers operating at 1550 nm in dispersion-decreasing fibers (DDF's). High-quality soliton compression from 630 down to 115 fs in a 100-m DDF and from 3.5 down to 230 fs in a 1.6-km DDF is obtained. The effects of third-order dispersion and Raman self-scattering on the compression process are observed and discussed.

Nonlinear soliton propagation in a dispersion-decreasing fiber (DDF) has long been thought of as a promising technique for the compression of soliton pulses.[1,2] It has been shown theoretically that the DDF compression technique not only provides high-quality compression of picosecond soliton pulses but can also permit the generation of extremely short (~20-fs) pulses.[3,4] Recent developments have been made in the fabrication of DDF's based on a technique involving the tapering of silica-based fibers during the pulling process.[2] Such fibers are suitable for use in the wavelength range of 1.4–1.7 μm and have great potential for use in conjunction with mode-locked erbium-doped fiber soliton lasers operating around 1.55 μm.[5,6] The first evidence of compressive effects in DDF's was obtained in experiments with ~100-fs solitons generated through the Raman self-scattering (RSS) effect.[4] The first direct measurements in both the temporal and spectral domain of the effect were obtained in recent experiments with picosecond solitons.[7] High-quality compression with compression factors as high as 16 were obtained.

In this Letter we report an experimental investigation of the adiabatic compression of solitons in DDF's. Self-starting, passively mode-locked, erbium fiber figure-eight lasers and nonlinear polarization-evolution ring lasers were used as the sources of both picosecond and subpicosecond soliton pulses. Soliton compression was studied in two DDF's having different lengths and dispersion characteristics, which enabled us to examine the compression behavior over various operating regimes. The influence of RSS and higher-order dispersion effects is observed and discussed. The experimental configurations presented demonstrate the suitability of the combination of a DDF and a passively mode-locked erbium fiber laser for ultrashort pulse generation.

We selected a passively mode-locked figure-eight erbium fiber laser[5,6] as a source of subpicosecond solitons. The experimental configuration is shown in Fig. 1. In order to provide sufficient pulse energy at the laser output, the 90% laser output coupler was placed immediately after the laser gain section. In this configuration, the fiber laser generated 630-fs transform-limited soliton pulses at 1558 nm and, by appropriate pump-power control, could be made to operate at the fundamental frequency (5 MHz). The spectrum and autocorrelation trace of typical pulses measured directly at the laser output are shown in Figs. 2(a), top, and 2(b), top. The suppression of additional cw components from this particular laser proved difficult with such a high output coupling, and the pulse spectra were often accompanied by additional sharp cw spectral features [see Figs. 2(b), middle, and 2(b), bottom]. Neither the cw components nor the low-intensity sidelobes characteristic of such lasers [see Fig. 2(a), top] were found to affect the compression process. An in-line optical attenuator was spliced between the output coupler and the DDF in order to allow us to adjust precisely the peak power of the pulses launched into the compressor.

Two DDF's were available, DDF1 and DDF2. Initially, we used DDF1, which had a length of 100 m. The dispersion of DDF1 (as measured at 1.55 μm) was 10 ps nm^{-1} km^{-1} at the input and tapered down to 1.4 ps nm^{-1} km^{-1} at the DDF output. The dispersion-length profile of the fiber was designed to be hyperbolic.

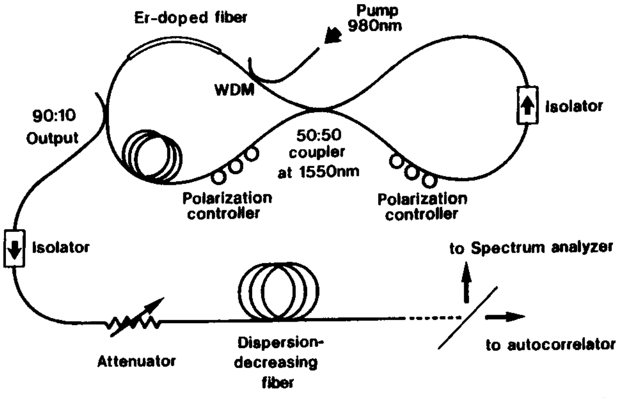

Fig. 1. Experimental configuration of the figure-eight laser and the DDF pulse compressor. WDM, wavelength-division multiplexer.

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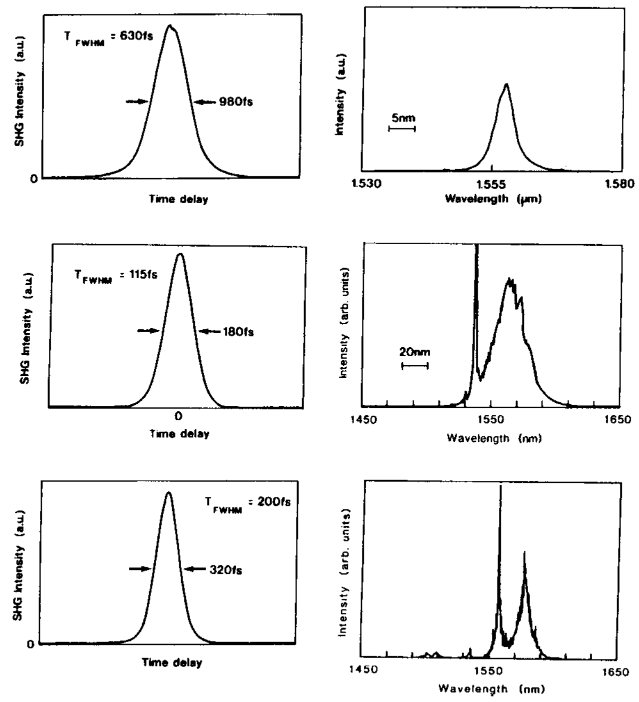

(a) (b)

Fig. 2. (a) Autocorrelation traces and (b) optical spectra of 630-fs soliton at the figure-eight laser output (top), 115-fs solitons at the 100-m DDF output (middle), and 200-fs solitons at the 1.6-km DDF output (bottom). SHG, second-harmonic generation.

The choice of this 100-m DDF for compression of 630-fs solitons is based on the simple theoretical considerations formulated in Refs. 2 and 8, where it was shown that soliton propagation in a DDF can be considered as formally analogous to soliton propagation in a fiber with steady amplification along its length. The length of uniformly amplifying fiber L_{amp} (dispersion $= k_2^{\mathrm{inp}}$, the input dispersion of the DDF, and amplification over the full length W) that is equivalent to a length of dispersion-decreasing fiber L_{DDF} (assuming hyperbolically decreasing dispersion) is given by $L_{\mathrm{amp}} = L_{\mathrm{DDF}} \ln(W)/(W - 1)$. Here $W = k_2^{\mathrm{inp}}/k_2^{\mathrm{out}}$ and k_2^{out} is the dispersion at the DDF output. For our 100-m DDF, $W \approx 7$, and the equivalent amplifier length is $L_{\mathrm{amp}} = 33$ m. The dispersion length z_0 of the 630-fs solitons at the fiber input is $z_0 = 0.322{t_0}^2/k_2^{\mathrm{inp}} = 10$ m. The differential field amplification coefficient G (in soliton units) for the initial soliton of half-width $t_0 = 630$ fs is given by $G = 0.5z_0 \ln(W/L_{\mathrm{amp}}) = 0.29$. The numerical simulation carried out in Ref. 8 indicates that the soliton energy is trapped and that adiabatic compression is obtained for small values of G. The simulations show that high-quality compression should be expected for $G = 0.29$.

The results of measurements at the DDF output, when the exact soliton power corresponding to the input DDF dispersion and mode parameters was launched, are shown in Figs. 2(a), middle, and 2(b), middle. The autocorrelation trace has a good sech^2 form and has no pedestal. The width is 180 fs and corresponds to a soliton duration of 115 fs. The optical spectrum is seen to broaden from 4 to 22 nm. The pulses are seen to have remained at the transform limit (time–bandwidth product = 0.32 in both instances). The compression process is accompanied by a 5-nm spectral shift owing to RSS. Note that the additional spectral line observed at 1.536 μm in Fig. 2(b), middle, was not associated with the compression process and is simply an additional cw laser component.

This experiment demonstrates adiabatic soliton compression from 630 down to 115 fs, corresponding to a compression factor of ~5.5, which is slightly lower than the predicted value based on the simple theory above. This discrepancy can be explained by taking into account RSS and higher-order dispersion effects. Owing to the soliton frequency shift, the output dispersion at the shifted frequency is given by $k_2^{\mathrm{out}}(\Delta w) = k_2^{\mathrm{out}} + k_3 \Delta w$, where Δw is the frequency shift and k_3 is the third-order dispersion. For this particular DDF, k_3 does not vary significantly along the fiber length and has the ordinary positive value of 0.07 ps nm^{-2} km^{-1}. We therefore estimate the output dispersion at the shifted frequency as ~1.7 ps nm^{-1} km^{-1}, leading to an estimate of 5.8 for the expected compression factor, in good agreement with the experimentally observed value.

In a second experiment, we examined the compression of the 630-fs pulses in a second DDF of length 1.6 km. The dispersion at 1550 nm tapered from 10 ps nm^{-1} km^{-1} at the input down to 0.5 ps nm^{-1} km^{-1} at the output. Compression of the pulses down to 200 fs was obtained [see Figs. 2(a), bottom, and 2(b), bottom]. In this case, the fiber length is too long for optimal compression of subpicosecond solitons, the soliton spectrum shifts by 25 nm during propagation, and the effective compression factor is reduced to 3.2. It has been shown[4] that the interplay between the RSS and third-order dispersive effects leads not only to a decrease in the effective femtosecond soliton compression factor, but also to the effect of pulse-width stabilization in the DDF. Stabilization means that compression can only be obtained down to a limiting minimum pulse width. This limiting value is essentially independent of the input pulse width and determined solely by the DDF characteristics.

The spectrum shown in Fig. 2(b), bottom, can be seen to contain a number of peaks. The peaks at 1532 and 1557 nm are additional cw components emitted by the figure-eight laser. The spectral components around 1500 nm arise as a result of the DDF soliton compression. The phenomenon was particularly well illustrated by our experiments on picosecond soliton compression. In these experiments, a passively mode-locked erbium fiber ring laser[7,9] was used as a source of transform-limited soliton pulses with durations in the range 2–4 ps at wavelengths around 1.55 μm. We examined only compression in the 1.6-km DDF, the 100-m fiber being of an inappropriate length for picosecond soliton compression. In Fig. 3(a) we show the spectrum and in Fig. 3(b) the autocorrelation trace of 230-fs pulses obtained at the DDF output as a result of the compression of

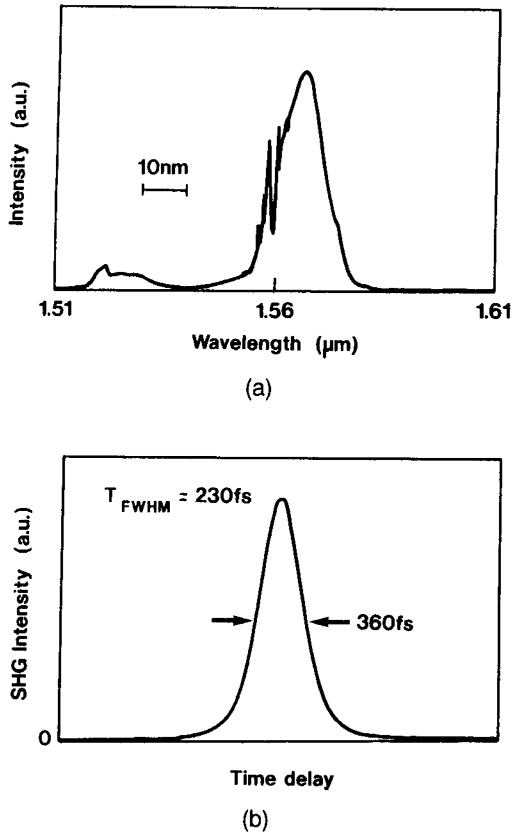

Fig. 3. (a) Spectrum and (b) autocorrelation function resulting from 3.5-ps soliton pulse compression in the 1.6-km DDF.

3.5-ps pulses. The compression factor of 16 that was obtained indicates that this fiber is close to optimum for picosecond pulses and provides high-quality pulse compression. The compression process is accompanied by both a 10-mn spectral shift owing to the Raman self-frequency shift and by the appearance of the anti-Stokes spectral components near 1520 nm.

The origin of such anti-Stokes spectral components was previously predicted in numerical simulations of femtosecond soliton compression in DDF's.[4,10] It is interesting to note that the spectral shape is almost identical, right down to the finest details, to the simulation data presented in Ref. 11 calculated for a similar system. The anti-Stokes generation is physically associated with soliton propagation in the vicinity of the zero of second-order dispersion. Computer simulations show that when a soliton propagates in an ordinary fiber having second- and third-order dispersions $k_2(w)$ and $k_3(w)$, respectively, at soliton mean frequency w, a narrow peak is generated in the spectral domain, separated by $\Delta w = 3k_2(w)/k_3(w)$ from the soliton mean frequency. In the time domain, this radiation constitutes a dispersive wave propagating in the positive group-velocity-dispersion region, with a different group velocity for the soliton. The process is effective only when the soliton propagates close to the zero-dispersion wavelength. The closer and wider the soliton spectrum, the stronger the influence of the third-order dispersion. Since the second-order dispersion decreases with length in a DDF and the third-order dispersion remains approximately constant, the frequency shift of the anti-Stokes component changes with position along the fiber. This effect ultimately gives rise to the generation of a wide spectrum.

We believe that the effect can be physically interpreted as an anti-Stokes parametric amplification process. The pump and Stokes waves are contained within the soliton spectrum. The phase-matching condition is satisfied, since all spectral components of the soliton have the same phase, whereas the optical wave shifted by Δw has the same phase propagation constant, or phase velocity, as the soliton itself. Such a mechanism qualitatively explains all the features of the process. A more detailed discussion lies outside the scope of this Letter.

In conclusion, we have investigated the adiabatic soliton compression of soliton pulses in various operating regimes for both subpicosecond and picosecond soliton pulses. The effects of RSS and third-order dispersion on the compression process were observed and discussed. We experimentally observed for what is to our knowledge the first time the generation of anti-Stokes radiation accompanying soliton propagation in the vicinity of the zero of second-order dispersion. As our experiments show, the DDF compression technique is ideally suited for use in conjunction with erbium fiber soliton lasers. The technique is extremely simple and provides stable, high-quality, polarization-insensitive compression. Ultimately this technique should lead to the development of simple diode-pumpable circuits capable of entering well into the sub-100-fs regime.

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