10-GHz 1.3-ps Pulse Generation Using Chirped Soliton Compression in a Raman Gain Medium

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***Abstract*—The authors demonstrate a novel pulse compression technique that is capable of producing high-quality 1.3-ps pulses at a repetition rate of 10 GHz. The technique begins with 20-ps pulses carved by a commercially available external modulator and achieves up to 15-fold compression using a combination of phase modulation and distributed Raman amplification. Unlike adiabatic soliton compression, the scheme takes advantage of an exact solution to the nonlinear Schrödinger equation for chirped soliton evolution. As such, high-quality low-pedestal compressed pulses can be produced in a shorter span of fiber than would be needed for adiabatic compression. Because the system uses external modulation, the source is inherently tunable. Furthermore, the degree of pulse compression can be adjusted by varying the amount of Raman gain and phase modulation.**

***Index Terms*—Distributed amplifiers, optical fiber amplifiers, optical propagation in nonlinear media, optical pulse compression, optical pulse generation, optical solitons, Raman scattering.**

I. INTRODUCTION

RELIABLE and flexible short pulse sources are important for current and future high-speed optical communication systems. In particular, optical time-division multiplexed systems use short pulse sources for transmitting data [1], performing all-optical logic, and demultiplexing [2] and optical clock recovery [3].

Several techniques have been developed to produce optical pulses, including modelocking [4], gain-switching of distributed feedback (DFB) lasers [5], direct modulation using electroabsorption modulators [6], [7] and electrooptic modulators [8], and supercontinuum generation [9]. Much research has been devoted to adiabatic soliton compression, in which a fundamental soliton evolves adiabatically into a shorter soliton either in a region with distributed gain [10], [11] or (equivalently) decreasing dispersion [12], [13]. In adiabatic compression, the gain must be gradual on the timescale of the soliton period, which means that the required length of fiber grows quadratically with the initial pulsewidth [14].

We demonstrate here a new type of pulse compression that utilizes a combination of chirp compensation and nonlinear soliton effects. The technique, which was proposed earlier and numerically simulated [15], takes advantage of exact solutions to the nonlinear Schrödinger equation (NLSE) for chirped solitons. We show that with this technique it is possible to achieve efficient 15-fold compression from initial pulsewidths greater than 20 ps in a length of fiber much shorter than would be required for adiabatic soliton compression.

II. THEORY

The nonlinear Schrödinger equation, expressed in a reference frame moving at the group velocity, is

$$\frac{\partial u}{\partial z} = \frac{\alpha}{2}u + \frac{j}{2}\beta_2\frac{\partial^2 u}{\partial t^2} - j\gamma|u|^2u \tag{1}$$

where u is the field envelope, α is the z-dependent gain coefficient, β_2 is the group velocity dispersion (assumed to be negative), and γ is the nonlinear coefficient. In the special case that the gain $\alpha(z)$ is of the form [15]

$$\alpha(z) = \frac{\alpha_0}{1-\alpha_0 z}. \tag{2}$$

Equation (1) admits solutions which are chirped solitons

$$u(z,t) = \sqrt{\frac{|\beta_2|}{\gamma T^2}}\,\mathrm{sech}\left(\frac{t}{T}\right)\exp\left(\frac{jCt^2}{2T^2}\right)\exp(j\phi) \tag{3}$$

where T, C, and ϕ are functions of z. The pulsewidth T and normalized chirp parameter C decrease linearly with distance according to

$$T(z) = T_0(1-\alpha_0 z), \tag{4}$$

$$C(z) = \frac{T_0^2\alpha_0}{|\beta_2|}(1-\alpha_0 z). \tag{5}$$

By making a suitable change of variables [14], the above solution can be translated into another solution in which there is no gain or loss ($\alpha = 0$), but the dispersion decreases exponentially with distance, as do the pulsewidth and normalized chirp.

These solutions have many of the features of adiabatic soliton compression: the pulse shapes and energies at the input and output are identical to that of a fundamental soliton, and the degree of pulsewidth compression is equal to the total gain of the span, or the ratio of the input to the output dispersion. The difference is that the chirped solitons represent an exact solution to (1), whereas adiabatic soliton compression can only occur if the gain is distributed over a sufficiently large distance. With chirped soliton compression, the same amount of pulse compression can therefore be achieved in a shorter span of fiber.

Because the input pulse is not transform-limited, it is possible to first compress the pulse via linear techniques followed by nonlinear adiabatic soliton compression [13]. Instead, the technique reported here combines both linear and nonlinear com-

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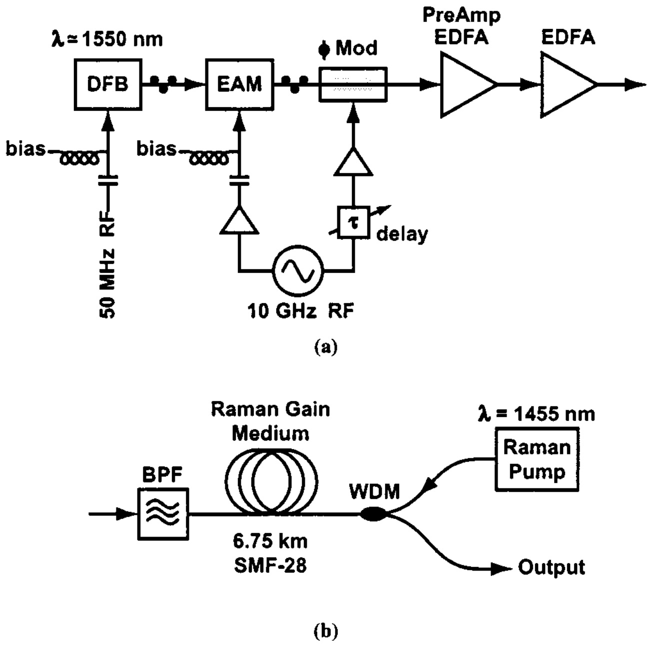

Fig. 1. (a) Setup used to produce chirped solitons. An electroabsorption modulator produces 20-ps pulses, which are chirped by an electrooptic phase modulator. (b) The pulse compression then occurs in a counterpumped Raman gain medium.

pression in the same span of fiber, both effects occuring simultaneously.

III. Experiment

Fig. 1(a) depicts the experimental setup used to generate chirped solitons at 1550 nm. The pulses are produced by external modulation of a conventional DFB laser, which makes it relatively easy to change the wavelength of the source by tuning or exchanging the laser. The electroabsorption modulator is a commercially available model (JAE FOEA-230-002) which produces ~20-ps pulses with a small negative chirp. The electrooptic phase modulator is used to impose a positive chirp on the pulses from the electroabsorption modulator. A variable radio frequency (RF) attenuator (not depicted) is used to control the degree of phase modulation. The relative timing of the phase modulation is adjusted with an RF delay while observing the output optical spectrum, to ensure that the pulse is aligned with the peak of the phase modulation. To suppress the effects of stimulated Brillouin scattering, a −23-dBm dither signal at 50 MHz was applied to the laser to broaden the linewidth.

Fig. 1(b) depicts the pulse compression medium. Although it is difficult to achieve exactly the gain profile described by (2), one can approximate it using counterpumped Raman amplification, in which pump attenuation and depletion produce an optical gain α which increases with distance. In our system, the gain is distributed over a span of 6.75 km of Corning SMF-28 fiber with a dispersion of 17 ps/nm·km. The Raman pump laser operates at a wavelength of 1455 nm and is injected in the counterpropagating direction using a wavelength-division-multiplexing (WDM) coupler. The maximum available pump power is 3 W. A bandpass filter at the input serves the dual purpose of blocking any remaining pump power and filtering unwanted ASE noise from the input signal.

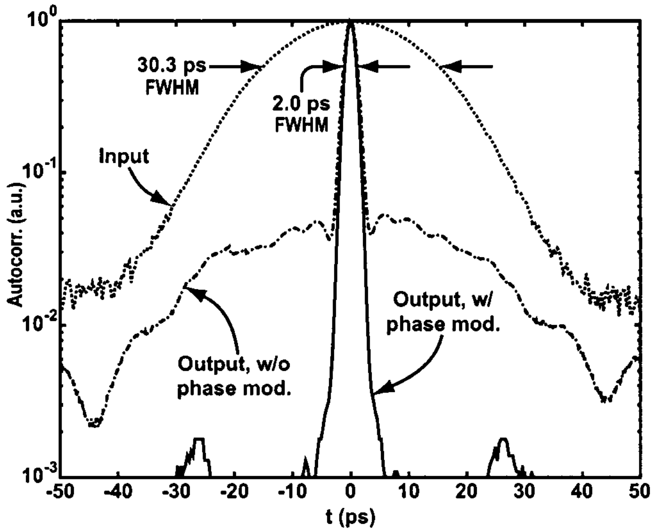

Fig. 2. Input and output intensity autocorrelation, measured using a background-free autocorrelator, showing 15-fold pulsewidth compression. When the phase modulator is disabled, the system resembles a conventional adiabatic soliton compression system. In this case, the output autocorrelation shows a clear pedestal, which occurs when the adiabatic condition is not met.

Fig. 2 shows the intensity autocorrelation of the input pulses and the output pulses after compression, measured using a background-free autocorrelator. The input pulses have an autocorrelation full-width at half-maximum (FWHM) of 30 ps, from which we infer an input pulsewidth of 20 ps. The average input power at the beginning of the span was 14.5 dBm, which in the absence of phase modulation was found to satisfy the condition for creating a fundamental soliton. The Raman pump power was 2.28 W, which created a gain of about 12.5 dB in the fiber. The peak-to-peak magnitude of the applied phase modulation was 6.5 radians, which gives rise to a normalized chirp parameter of about $C = 0.80$. The measured output autocorrelation shown by the solid curve in Fig. 2 has a FWHM of 2.0 ps, which for a soliton corresponds to a pulsewidth of 1.3 ps.

When the phase modulator is disabled, the input pulse closely approximates an unchirped, $N = 1$ soliton, and the system therefore is similar to conventional adiabatic compression. However, in this case the adiabatic condition is not met and the output pulse exhibits a large pedestal, as shown in the semidashed curve in Fig. 2.

Fig. 3 depicts the measured optical spectra of the chirped input pulses and the output pulses. The input spectrum is consistent with a chirp of 0.80. The solid line over the output spectrum shows a least squares fit to a $\mathrm{sech}^2(\cdot)$ function, from which we estimate the output spectral width to be 250 GHz. Based upon this measurement, the time-bandwidth product of the output pulses is 0.32, indicating that they are close to transform limited. That is consistent with (5) which predicts that the chirp should decrease by the same factor as the pulsewidth. Based upon numerical simulations of the system, we believe that the observed deviations from the anticipated $\mathrm{sech}^2(\cdot)$ spectrum are explained by nonoptimal launch conditions.

We have repeated the above measurements using different lasers ranging in wavelength from 1547 to 1558 nm, with essentially identical results. The tunability of the system is lim-

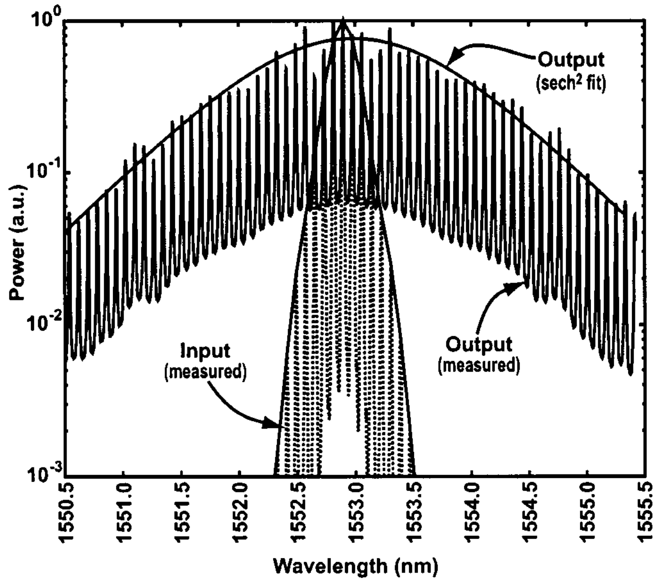

Fig. 3. Measured optical spectra of the input and output signals. The comb-like frequency response shows the 10-GHz repetition rate. Both spectra have been normalized to a peak value of 1.

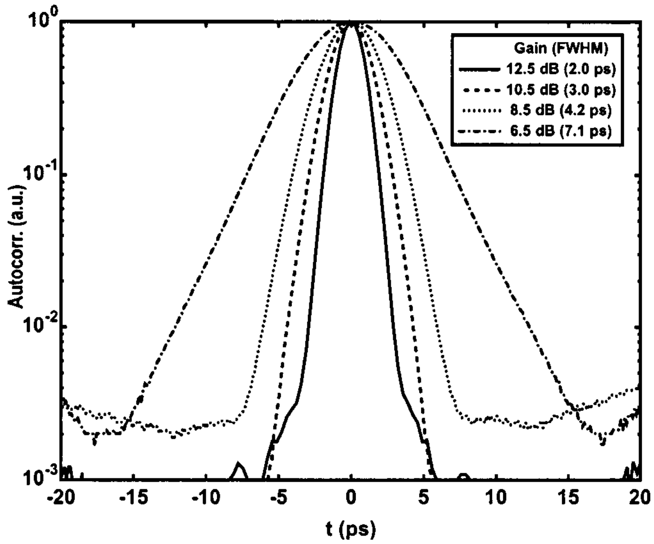

Fig. 4. Measured output autocorrelations for four different gains. The pulsewidth can be adjusted by varying the Raman pump power, which in turn changes to total gain experienced by the signal. In each case, the input phase modulation was adjusted to achieve the best possible pulse shape. The longer pulses show a slightly higher background level because the system was not optimized for these pulsewidths.

ited by the optical operating bandwidth of the electroabsorption modulator and the gain of the erbium-doped fiber amplifiers. By replacing the electroabsorption modulator with an electrooptic modulator, we could potentially expand the tunability of the source.

The output pulsewidth can also be adjusted by varying the Raman pump power. Fig. 4 shows four different output autocorrelation measurements, corresponding to different Raman gains. In each case, the amplitude of the phase modulation was adjusted to give the optimal output pulse characteristics.

IV. CONCLUSION

We described and demonstrated a new pulse compression system which uses chirped solitons and distributed Raman amplification. The system has been shown to provide more than 15-fold pulsewidth compression in a span of fiber shorter than that required by adiabatic compression. The source is constructed using commercially available components and allows for both wavelength and pulsewidth tunability.

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