114 Gbit/s soliton train generation through Raman self-scattering of a dual frequency beat signal in dispersion decreasing optical fiber

S. V. Chernikov and E. M. Dianov
General Physics Institute, 38 Vavilova Street, Box 117333, Moscow, Russia

D. J. Richardson, R. I. Laming, and D. N. Payne
Optoelectronics Research Centre, Southampton University, Southampton, SO9 5NH, United Kingdom

(Received 21 December 1992; accepted for publication 4 May 1993)

We report the generation of 114 Gbit/s trains of 250 fs fundamental solitons. The pulses are generated due to the conversion of an intense optical beat signal (generated from two DFB laser diodes and an erbium doped fiber amplifier combination) into a soliton train due to nonlinear propagation in a 1.6 km fiber of steadily decreasing dispersion. The train repetition rate corresponds to the beat frequency of the input signal and was readily tunable between 80 and 120 GHz. The results of a computer simulation of the system are found to be in good qualitative agreement with the experimental observations.

Methods for high repetition-rate pulse train generation based on nonlinear propagation of an optical signal along an optical fiber can be considered as an alternative technique to the traditional sources of short optical pulses—namely, actively or passively mode-locked lasers. Pulse trains can be obtained using the effect of induced modulation instability. In this instance, a powerful cw monomode beam with a small amplitude modulation breaks up into a train of short pulses as it propagates in an optical fiber.[1,2] However, in this case, the pulses generated have a large frequency modulation and are far from transform limited. In addition, they are accompanied by a significant pedestal. It has recently been shown theoretically[3] that under the combined effect of modulation instability and Raman self-scattering (RSS)[4] a train of pure solitons with durations of a few hundred femtoseconds can be obtained at repetition rates in the 100 GBit/s regime. In this case, a train of short femtosecond pulses is generated due to modulational instability, and subsequently Stokes-shifted solitons are formed due to the RSS. Another promising technique for the generation of high-repetition rate cw trains of well-separated solitons has recently been suggested[5] and experimentally realized.[6,7] The technique is based upon the transformation of a dual-frequency beat signal into a train of solitons as a result of nonlinear propagation in an optical fiber providing either slow amplification, or steadily decreasing dispersion along its length.

In this letter we demonstrate the generation of a high repetition-rate train of femtosecond solitons using a new approach. The technique is based on the instability of a dual-frequency beat signal propagating in a dispersion decreasing fiber (DDF) combined with the effect of RSS. Using a DDF of 1.6 km length, we have obtained 80–120 Gbit/s trains of 250 fs fundamental solitions. The technique presented here utilizing RSS differs fundamentally from the previously reported DDF techniques[4–7] based on the adiabatic transformation of a beat signal and permitted us to generate significantly shorter pulses.

The experimental configuration is illustrated in Fig. 1. The outputs from two, pig-tailed, single frequency DFB lasers (DFB1 and DFB2) were combined using a 3 dB coupler to create a beat signal. The lasers emitted at wavelengths around 1550 nm. The temperature of the laser diodes could be independently varied to a high accuracy enabling the laser wavelength separation to be tuned between 0 and 2 nm. The beat signal was then passed through a polarization-sensitive isolator into an erbium-doped fiber amplifier (EDFA) with a counter-propagating pump. Polarization controllers were included in both input leads to the combining coupler in order to maximize and equalize the relative intensities of the light from the DFB lasers passing through the isolator. The EDFA fiber was based on a silica-germano-alumina host, contained 160 ppm Er^{3+}, and had a length of 35 m. A Ti:sapphire laser operating at 978 nm was used for pumping of the EDFA. The pump radiation was coupled into the EDFA via a WDM coupler, and the input pump power was stabilized using a servo circuit and Bragg cell placed in front of the launch optics. The amplified beat signal was then passed through a second isolator which prevented feedback into the EDFA from the rest of the system. Up to 300 mW of amplified power was available at the isolator output. However, in order to increase the peak amplified power level, the beat signal coupled into the EDFA was modulated to reduce the amplifier saturation (square pulses modulation, 100 ns

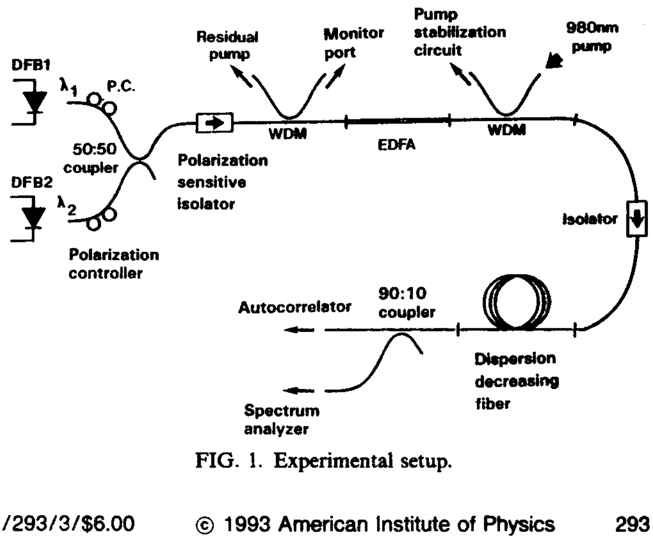

FIG. 1. Experimental setup.

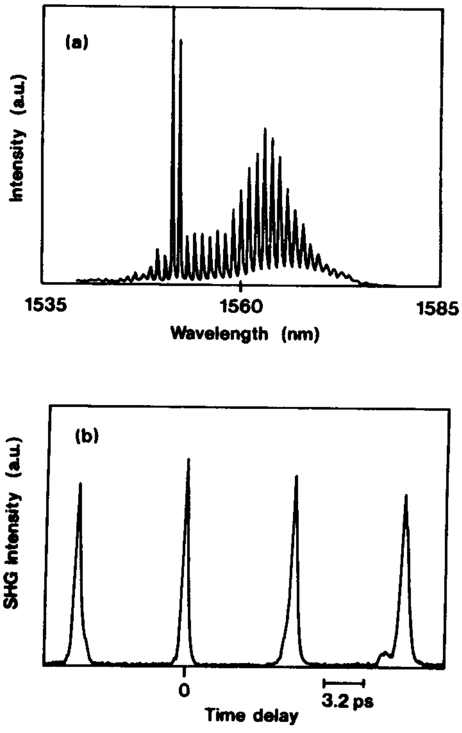

FIG. 2. Experimental spectrum (a) and autocorrelation trace (b) of 114 Gbit/s soliton train obtained at the end of the DDF fiber.

pulses at 300 kHz). The modulation was provided by direct synchronous modulation of the laser diode drive current and permitted an amplified peak power of up to ~800 mW within the 100 ns pulses. The level of the power between pulses was less than 60 mW and was due to the amplified spontaneous emission, peaking at 1535 nm.

The amplified beat signal was coupled into a DDF which was spliced to the isolator output. The DDF length was 1.6 km. The fiber was fabricated using a recently developed technique.[8] The dispersion at 1550 nm varied along the fiber length from $D_{\text{inp}}=10$ ps/nm/km to $D_{\text{out}}=0.5$ ps/nm/km. The dispersion length profile was designed to be close to a hyperbolic form. A 90:10 coupler was spliced to the DDF output to facilitate real-time measurement of the spectrum and background-free intensity autocorrelation function.

A typical spectrum and autocorrelation trace of the soliton train as generated by the technique at the output of the DDF are shown in Figs. 2(a) and 2(b), respectively. The launched 978 nm pump power was estimated to be 700 mW. The spectrum of the amplified beat signal at the DDF input consisted of two single frequencies around 1551 nm separated by ~0.9 nm. The autocorrelation trace at the DDF input had a sinusoidal form with a period of 8.6 ps. The ratio of the SHG intensity minimum to maximum was 3 to 1.

The output spectrum consisted of many equally spaced spectral lines as expected for a high frequency, periodic signal. The spectrum consists of two separated parts. The first is shifted in frequency toward the longer wavelength and has a pulse-shape envelope with a maximum at 1565 nm and half-maximum of ~10 nm. This spectral component corresponds to a train of spectrally shifted solitons, generated through the RSS. The other spectral component is a remnant signal centered around the initial wavelength 1551 nm. The autocorrelation function [Fig. 2(b)] clearly demonstrates the generation of a 114 Gbit/s train of well separated pulses. The Stokes-shifted soliton train contains more than 80% of the full signal energy. There is no intrapulse background, however, one can see the appearance of additional peaks in the autocorrelation trace. These peaks appear to be related to residual radiation at the initial wavelength. The duration of the central autocorrelation peak is 360 fs corresponding to a soliton width of 230 fs. The bandwidth of a 230 fs soliton is 10 nm, in agreement with that determined from the half-width of the Stokes-shifted spectral envelope.

The technique permits us to tune the repetition rate of the soliton train simply by adjusting the frequency and intensity of the input beat signal. These parameters are readily controlled by adjusting the frequency and intensity of the DFB lasers, respectively. The repetition rate could be tuned between 80 and 120 GHz with this single configuration, the pulse duration remaining in the range 230–300 fs. Although the Stokes frequency shift of the generated soliton train depends on the input power and beat frequency, the output frequency was reasonably stable (the instability was considerably less than the repetition frequency).

For a theoretical interpretation of the results obtained, we carried out a numerical simulation of the system. The simulation was based on the nonlinear propagation equation for the dimensionless field envelope $\Psi(\tau,\xi)$ which takes into account the effects of decreasing fiber chromatic dispersion, third-order dispersion, and the fiber nonlinearity [the self-phase modulation (SPM) and Raman effects]:[9–11]

$$i\frac{\partial\Psi(\tau,\xi)}{\partial\xi}+\frac{d_2(\xi)}{2}\frac{\partial^2\Psi(\tau,\xi)}{\partial\tau^2}-i\frac{d_3}{6}\frac{\partial^3\Psi(\tau,\xi)}{\partial\tau^3}$$
$$+\Psi(\tau,\xi)\int_{-\infty}^{\tau}|\Psi(\tau-\tau',\xi)|^2F(\tau-\tau')d\tau'=0,$$

where the dispersion length profile $d_2(\xi)=1/(1+12\xi)$ for $0<\xi<L(L=1)$ is close to that used in the experiments, and the nonlinear response function $F(\tau-\tau')=(1-a)\delta(\tau-\tau')+aR(\tau-\tau')$ where $a=0.18$ and which takes into account both the instantaneous and delayed Raman response $R(\tau-\tau')$.[9,10] The input beat signal was $\Psi(t,0)=b\sin(\pi t/T)$. In Fig. 3 we present a typical pulse train and corresponding optical spectrum and in Fig. 4 we plot the peak power and pulse duration evolution against propagation length as calculated from the simulation.

The mechanism of soliton pulse generation from the beat signal half-periods in this case was found to be similar to the effect of Raman self-scattering of multisoliton pulses[11,12] as well as to that of the combined effect of the modulational instability and RSS.[3] Briefly, at the initial stage of propagation SPM dominates the signal evolution. This leads to frequency modulation at the beat signal half-period and results in compression. As the dispersion decreases along the fiber the compressive effect is enhanced

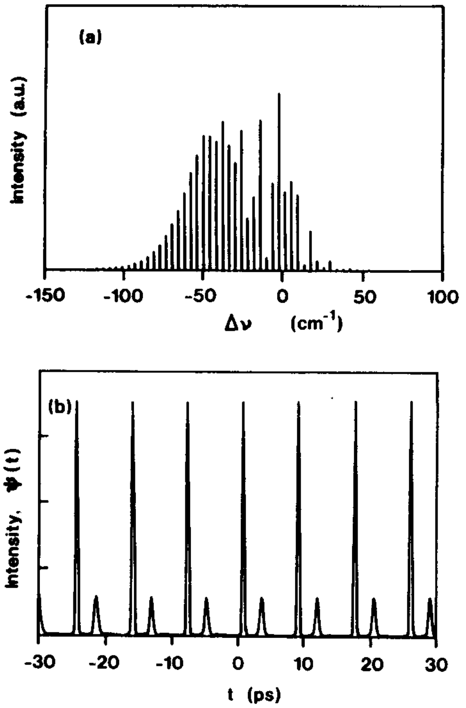

FIG. 3. (a) Spectrum and (b) intensity profile of the generated soliton train as obtained from numerical simulations of the experimental system. The dimensionless parameters used in the simulation are $b=2.8$, $T=2$, and $t=4.3$ ps.

and results in further broadening of the spectra and ultimately in the generation of a short pulse train and an accompanying pedestal. Since the pulse duration at the minimum ($\xi=0.4$) is as short as 350 fs (Fig. 4), the RSS effect becomes significant and results in a red shift of the short pulse spectral component. As the soliton pulses and residual radiation have different mean wavelengths and consequently different group velocities, the soliton train moves through the pedestal and is amplified by it through Raman amplification. The decreasing dispersion leads to further soliton compression. As a result, a periodic train of soliton pulses is generated containing most of the energy of the initial beat signal (Fig. 3). The residual energy is concentrated in a secondary train of longer duration pulses centered around the initial beat-signal wavelength. Only a negligibly small part is contained in a cw background. One can see that the theoretical results are in good qualitative agreement with the experimental measurements. The secondary pulses are responsible for the small additional peaks observed in the autocorrelation trace (see Fig. 2). Note, that if required, the generated soliton train can easily be spectrally filtered.

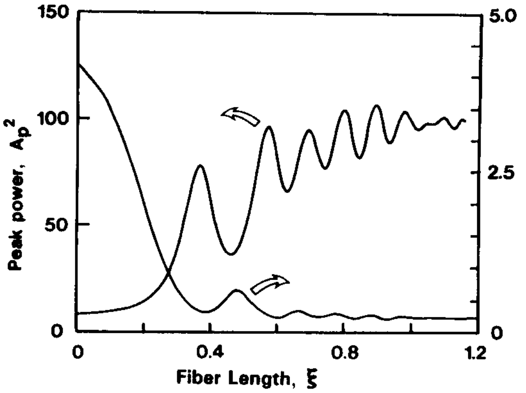

FIG. 4. Dynamical behavior of the pulse width and the peak power of the pulse train during propagation along the DDF as obtained from the numerical simulation of the system.

In conclusion, we have demonstrated a new technique for the generation of 100 Gbit/s soliton trains. The trains consist of well separated soliton pulses without pedestal. To our knowledge, this is the first source capable of generating pulses as short as 250 fs at such high repetition rates.

This work was funded in part by EEC RACE program R2015 (ARTEMIS). Two of us (D.J.R. and R.I.L.) wish to acknowledge the Royal Society for the provision of University Research Fellowships.

[1] A. Hasegawa, Opt. Lett. **9**, 288 (1986).
[2] K. Tai, A. Tomita, J. L. Jewell, and A. Hasegawa, Appl. Phys. Lett. **49**, 236 (1986).
[3] P. V. Marmyshev, S. V. Chernikov, and E. M. Dianov, Opt. Lett. **15**, 1365 (1990).
[4] E. M. Dianov, A. Ya. Karasik, P. V. Mamyshev, A. M. Prokhorov, V. N. Serkin, M. F. Stel'makh, and A. A. Fomichev, Piz'ma Zh. Eksp. Teor. Fiz. **41**, 242 (1985) [JETP Lett. **41**, 294 (1985)]; F. M. Mitschke and L. F. Mollenauer, Opt. Lett. **11**, 659 (1986).
[5] E. M. Dianov, P. V. Mamyshev, A. M. Prokhorov, and S. V. Chenikov, Opt. Lett. **14**, 1008 (1989); P. V. Mamyshev, S. V. Chernikov, and E. M. Dianov, IEEE J. Quantum. Electron. **27**, 2347 (1991).
[6] S. V. Chernikov, J. R. Taylor, P. V. Mamyshev, and E. M. Dianov, Electron. Lett. **28**, 931 (1992).
[7] S. V. Chernikov, D. J. Richardson, R. I. Laming, E. M. Dianov, and D. N. Payne, Electron. Lett. **28**, 1210 (1992); S. V. Chernikov, P. V. Mamyshev, E. M. Dianov, D. J. Richardson, R. I. Laming, and D. N. Payne, Sov. Lightwave Commun. **2**, 101 (1992).
[8] V. A. Bogatyrev *et al.*, IEEE Lightwave Technol. **9**, 561 (1990).
[9] G. P. Gordon, Opt. Lett. **9**, 662 (1986).
[10] R. H. Stolen, G. P. Gordon, W. J. Tomlinson, and H. A. Haus, J. Opt. Soc. Am. **6**, 1159 (1989).
[11] E. A. Golovchenko, E. M. Dianov, A. Ya. Karasik, P. V. Mamyshev, A. N. Pilipetskii, and A. M. Prokhorov, Kvantovaya Electron. (Moscow) **16**, 592 (1989) [Sov. J. Quantum Electron. **19**, 391 (1989)].
[12] P. Beaud, W. Hodel, B. Zysset, and H. P. Weber, IEEE J. Quantum. Electron. **QE23**, 1938 (1987).