High-quality optical pulse train generator based on solitons on finite background

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Received February 15, 2013; accepted March 23, 2013;
posted April 9, 2013 (Doc. ID 185446); published May 10, 2013

We report a simple method to exploit the typical properties of solitons on a finite background in order to generate high-repetition-rate and high-quality optical pulse trains. We take advantage of the nonlinear evolution of a modulated continuous wave toward localized structures upon a nonzero background wave in anomalous dispersive fiber. After a stage of nonlinear compression, a delay-line interferometer enables the annihilation of the finite background and simultaneously allows the repetition-rate doubling of the pulse train.

OCIS codes: (190.4370) Nonlinear optics, fibers; (190.5530) Pulse propagation and temporal solitons; (320.5540) Pulse shaping.

http://dx.doi.org/10.1364/OL.38.001663

Solitons on finite background (SFBs) are solutions to the nonlinear Schrödinger equation (NLSE) that are currently stimulating renewed and widespread attention. Even if their analytical expressions have been proposed for more than 25 years [1,2], these nonlinear structures have only been recently identified as promising prototypes of the infamous oceanic rogue waves. Indeed, due to the periodic exchange of energy between a continuous background and a localized structure, an initially small perturbation can exponentially grow into a brief and intense spike before disappearing. With the emergence of the field of optical rogue waves, theoretical and experimental works have confirmed that optical fibers represent an ideal testbed to easily generate and study SFB: Peregrine solitons [3], Akhmediev breathers (ABs) [4], and Kuznetsov–Ma (KM) solitons [5] have indeed been demonstrated, taking advantage of widely available components for ultrafast optics.

In this context, it sounds appealing to benefit from the strong temporal compression and peak-power increase undergone by an initial perturbation to generate ultrashort pulses and to answer the needs of highly demanding applications, such as optical sampling or ultrahigh-capacity transmissions. Indeed, pedestal and background-free picosecond pulse trains at repetition rates of several tens of gigahertz and with a low duty cycle are required. In this context, using the Kerr nonlinearity acting into an optical fiber has already been demonstrated to be a practical and cost-effective alternative to conventional onerous active mode-locking lasers, and several schemes have been demonstrated at various repetition rates [6,7]. But to date, except the strategies numerically discussed in [8] by Mahnke and Mitschke, no solution has been designed to take advantage of the specific features of the SFB and to eliminate the nonnegligible background.

Here we propose to fully exploit the nonlinear evolution undergone by a sinusoidal modulation with a finite background propagating along an optical fiber with anomalous dispersion. It has been theoretically shown that such an initial condition reshapes into ultrashort structures close to AB or KM solitons depending not only on the balance between dispersive and nonlinear effects, but also on the amplitude of the initial modulation [3,5]. Our purpose being to generate high-repetition pulse trains, it seems more natural to concentrate on the processing of AB that intrinsically exhibits a temporal periodicity. However, note that the present method could also be applied to a periodic train of KM solitons, as described in [5]. At the point of maximum compression, the initial beating at a frequency ω_{mod} is reshaped into the following field [1,2]:

$$\psi(t) = \sqrt{P_0}\frac{(1-4a)+\sqrt{2a}\cos(\omega_{\mathrm{mod}}t)}{\sqrt{2a}\cos(\omega_{\mathrm{mod}}t)-1}, \tag{1}$$

where P_0 denotes the average power of the initial signal and a is a normalized parameter given by $2a = 1-(\omega_{\mathrm{mod}}/\omega_c)^2$ with $\omega_c^2 = 4\gamma P_0/|\beta_2|$, β_2 and γ being the dispersive and nonlinear coefficients of the fiber, respectively.

An illustration of the pulse train obtained at the point of maximum compression for $a = 0.41$ is given in Fig. 1(a). The intensity profile clearly exhibits the ultrashort periodic structures with a low duty cycle [Fig. 1(a1)]. A peak power that is 12 times higher than the continuous background is achieved. The corresponding amplitude $\psi(T)$ [Fig. 1(a2)] outlines that the background has an opposite sign compared with the modulated part. The optical spectrum presents the triangular shape typical of AB [4] [Fig. 1(a3)].

Our original method to cancel the deleterious background is to exploit the π phase shift that exists between the pulsed part and the background. Compared to [8], our method is here purely linear. We use here an interferometer not only to double the repetition-rate [9] but also to annihilate the deleterious background by imprinting a controlled π phase shift. Panels (2) illustrate this process and show how the interferential operation appears as destructive for the deleterious background and constructive for the pulsed part. Indeed, after a first splitting stage into both identical replicas, the resulting pulse trains are delayed by half of the period as well as phase shifted by π. Finally, after recombination, the final pulse train $\psi_T(t)$ is given by the following expression:

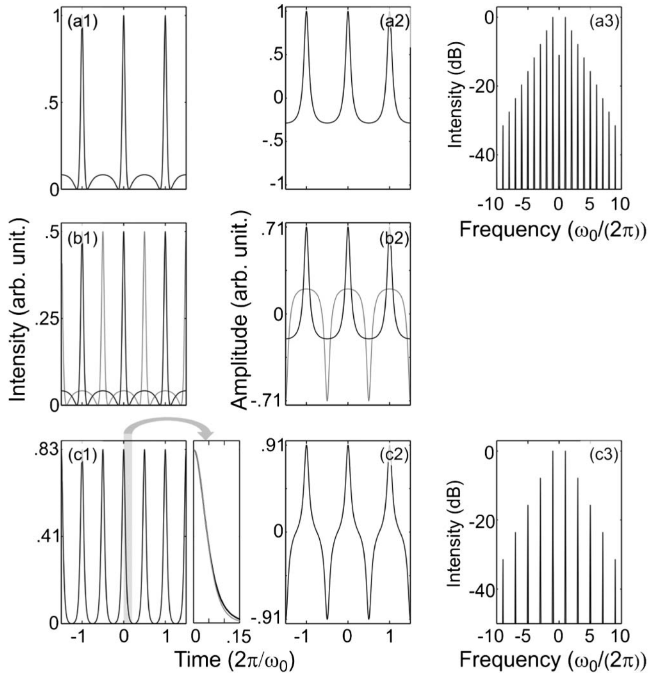

Fig. 1. Principle of frequency doubling and cleanup operations on a pulse train on a finite background. (a) Initial train of breathers. (b) Initial train of breathers (black line) and replica delayed by half of a period and phase shifted by π (gray line). (c) Resulting pulse train after recombination. The temporal intensity and amplitude profiles as well as the spectral intensity profiles are compared in panels 1, 2, and 3, respectively. In the magnification of (c1), the resulting intensity profile (black line) is compared with the temporal sech intensity profile of a soliton (gray line).

$$\psi_T(t) = \sqrt{P_0}\frac{4(1-2a)\sqrt{a}\,\cos(\omega_{\text{mod}}t)}{1-2a\cos^2(\omega_{\text{mod}}t)}, \tag{2}$$

and the temporal intensity profile reads as

$$P(T) = P_0\frac{16a(1-2a)^2\cos^2(\omega_{\text{mod}}t)}{1+4a^2\cos^4(\omega_{\text{mod}}t)-4a\cos^2(\omega_{\text{mod}}t)}. \tag{3}$$

From Eq. (3), one can make out that between two successive spikes of light, the intensity profile falls back to zero, confirming the total annihilation of the initially continuous background. The intensity profile is close to a hyperbolic secant profile [see magnification of Fig. 1(c1)], but as proven by Eq. (3) and the deviations observed in the wings of the pulsed part, the resulting field is no longer an exact solution of the NLSE. Our method therefore differs from the strategies discussed in [8] to convert AB into pedestal-free solitons. Regarding the peak power of the pulses, it obeys the simple equation: $16aP_0$.

In the spectral domain, as illustrated in Fig. 1(c3), our linear processing is equivalent to cancel one spectral component over two, which is a clear signature of the doubling of the repetition-rate. Note that our pulse train is therefore carrier suppressed, as confirmed by Fig. 1(c2): the amplitudes of the pulses have alternate signs.

In order to validate this concept, we have experimentally implemented the setup described in Fig. 2, which is based on cost-effective components that are widely used

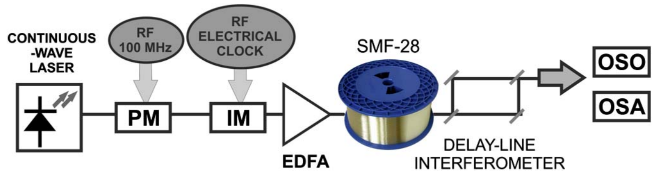

Fig. 2. Experimental setup.

for optical communications. A continuous wave (CW) emitted by an external cavity laser is phase modulated [phase modulator (PM)] to avoid Brillouin backscattering. The CW signal is then sinusoidally modulated by means of an intensity modulator (IM) driven by a 25 GHz RF beating. The amplitude of modulation is voluntary detuned so as to keep a nontotal extinction contrast [Fig. 3(a), dotted black line]. An erbium-doped fiber amplifier (EDFA) is then used in order to increase the average power up to 28 dBm. The reshaping of the sinusoidal beating into an SFB is achieved during the propagation in a 2.1 km standard single-mode fiber (SMF-28) with an anomalous dispersion of $-21\,10^{-3}$ ps^2/m and a nonlinearity of 1.1/W/km.

Both temporal and spectral intensity profiles of the resulting pulse train at the maximum of compression are characterized thanks to an optical sampling oscilloscope (OSO) with a picosecond resolution and an optical spectrum analyzer (OSA), respectively. Results are plotted in Fig. 3(a) with dotted gray lines and illustrate the nonlinear reshaping into picosecond pulses characterized by a significant part of the energy (25%) contained in a finite background, thus forbidding any practical application. The full width at half-maximum (FWHM) duration is 3.2 ps, indicating a 1/12.5 duty cycle. These experimental observations [Fig. 3(a2)] are in close agreement with the analytical results predicted from fiber and

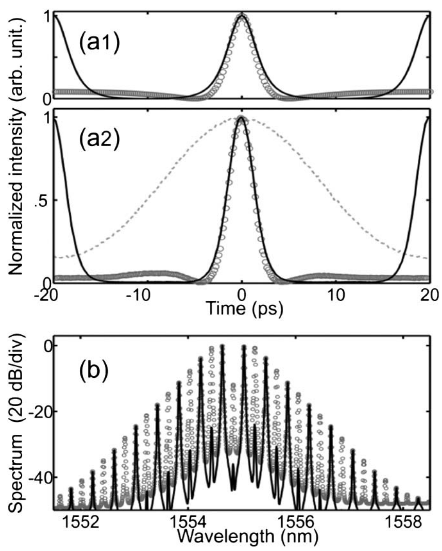

Fig. 3. Experimental results obtained for an input frequency of 25 GHz. Evolution of the temporal intensity profile over one period of the initial beat signal (plotted with gray dashed line): the pulse train emerging from the SMF (gray circles) is compared with the pulse train obtained after the DLI (solid black line). Analytical predictions from Eqs. (1)–(3) (a1) are compared with the experimental results (a2). (b) Corresponding experimental spectra.

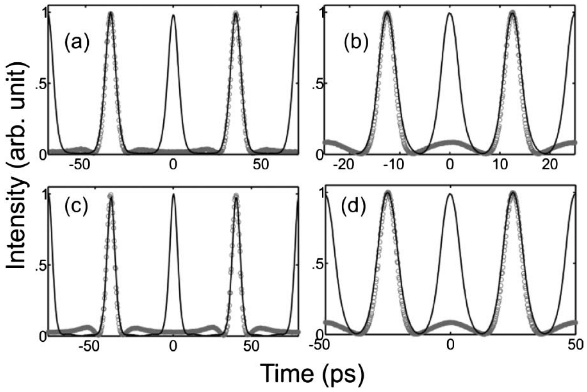

Fig. 4. Experimental results obtained for various repetition rates and fiber lengths. The temporal intensity profile over two periods of the pulse train emerging from the SMF (gray circles) is compared with the pulse train obtained after the DLI (solid black line). Results obtained by means of a 2.1 km long SMF for output repetition rates of (a) 28 GHz and (b) 80 GHz are compared with results obtained in 8 km for output frequencies of (c) 25 GHz and (d) 40 GHz.

initial signal properties with $a = 0.41$ [Fig. 3(a1)]. The optical spectrum exhibits the typical triangular shape expected for SFB.

The delay-line interferometer (DLI) relies on a mechanical delay line that provides a delay that is half the period of the pulse train. A piezo-electrical device incorporated in the interferometer imprints the requested π phase-shift. Results of the linear shaping are detailed in Fig. 3 by means of solid black lines and exhibit the efficient doubling of the repetition-rate combined with a significant enhancement of the pulse quality. Indeed, the level of the continuous background does not exceed 1% of the peak power and no noticeable pulse broadening occurs. The resulting duty cycle is therefore 1/6, which is comparable with the duty cycle usually obtained by means of other Kerr-nonlinearity-based techniques starting from an initial beating at $2\omega_{\mathrm{mod}}$ [6,7]. In the spectral domain, the central component is cancelled and the even harmonics disappear with an extinction ratio of 25 dB corresponding to the interferometer properties.

A significant benefit of our approach is the large flexibility of the device regarding its main characteristics, especially the range of repetition rates that can be processed with a fixed segment of fiber. Indeed, contrary to usual methods where the length of the fiber has to be carefully optimized to reach acceptable results, here the same fiber can be used to generate 28 GHz pulse trains [Fig. 4(a)] up to 80 GHz pulse trains [Fig. 4(b)] starting from 14 and 40 GHz electrical clocks, respectively. The level of input powers required to achieve such reshaping varies from 28 to 30 dBm for duty cycles between 1/6 and 1/3.

Other complementary experiments have been carried out with a longer SMF (length of 8 km) in order to achieve lower repetition rates at lower average powers. A selection of the results has been summarized in Figs. 4(c) and 4(d) and confirms that the principle of the method can be scaled to various repetition rates according to the properties of the fiber involved in the compression stage.

In summary, we have proposed and experimentally demonstrated an easy-to-implement linear shaping that enables us to take full advantage of the properties of SFBs. Taking advantage of the phase shift existing between the continuous background and the pulsed part of the SFB, the present interferential method allows us to efficiently remove the background in such a way to generate high-quality pulse trains cadenced at a twofold repetition-rate. Compared to other techniques based on the usual nonlinear reshaping of an initial beat signal into an optical fiber that are generally restricted to a particular set of parameters, the combination of SFB generation followed by interferential postprocessing offers a large range of tunability in repetition-rate and pulsewidth for a fixed segment of fiber, while keeping a high level of pulse quality.

We thank K. Hammani and G. Millot for stimulating discussions. We acknowledge the financial support of the Conseil Regional de Bourgogne (Pari Photcom) and the Agence Nationale de la Recherche (project SO FAST, ANR-11-EMMA-0005). We also thank the technical support of Photline Technologies for providing the interferometer.

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