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All-fibered high-quality 40-GHz to 200 GHz pulse sources based on nonlinear compression of besselons

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Abstract. We experimentally demonstrate the generation of pulse trains with repetition rates of 40-GHz, 80 GHz and 200 GHz. Our approach is based on the nonlinear compression of besselon pulses in a highly-nonlinear fiber with normal dispersion. The pulses are of high quality, with a subpicosecond duration.

1 Introduction

Generation of very low duty-cycle high-quality optical pulse trains at repetition rate of several tens of GHz around 1.5 µm has become increasingly interesting for many scientific applications such as optical sampling or ultrahigh capacity transmission systems based on optical time division multiplexing. Unfortunately, the current bandwidth limitations of optoelectronic devices do not enable the direct generation of pulses with temporal width below a few picoseconds. Actively mode-locked fiber lasers were found to be an efficient, but onerous option to overcome this limitation. Alternative cavity-free architectures have relied on nonlinear compression in optical fibers [1] or on the use of a quadratic spectral phase to process an initial sinusoidal phase modulation applied in the temporal domain on a continuous wave [2]. Recently, we have proposed to improve this last scheme by imprinting a triangular spectral phase profile instead of a quadratic one [3], which has enabled to generate a Fourier-transform limited waveform we named besselon [4]. When the optimum depth of phase modulation is chosen, the resulting pulse train exhibits a temporal profile that is very close from a Gaussian pulse with a duty cycle of 0.18.

We demonstrate here experimentally that it is possible to further compress the waveform by taking advantage of the spectral expansion occurring upon propagation in a highly nonlinear fiber. Subpicosecond pulses at a repetition rate of 40 GHz are demonstrated. Repetition rate doubling and quintupling is also achieved thanks to line-by-line spectral processing.

2 Principle and experimental setup

Our proposed method is based on a combination of linear and nonlinear processing using phase modulations both in the temporal and spectral domains. The experimental setup we implemented is sketched in Fig. 1. A continuous wave laser at 1550 nm is first phase-modulated (PM) in the temporal domain by a sinusoidal waveform with a depth of modulation of 1.3 rad and a frequency of 40 GHz. A linear spectral shaper is then inserted to imprint a triangular spectral phase profile namely a series of $\pi/2$ spectral phase shifts between each spectral component. This converts the initial phase modulation into a train of Fourier-transform limited pulses. For our initial phase modulation, the resulting besselon waveform is close to a high-quality Gaussian pulse that is not impaired by spurious background or sidelobes [3].

The second stage of our setup relies on the nonlinear expansion of the besselon spectrum. We therefore amplify the pulse train with an erbium doped fiber amplifier (EDFA) up to an average value of 27 dBm. We have found that the nonlinear propagation in a normally dispersive fiber followed by a dispersive anomalous device [5] provides the best temporal profiles with reduced pedestals. We used a fiber with a length of 1 km, a nonlinear coefficient of 10 /km/W and a normal dispersion of –0.7 ps/nm/km. In order to avoid the deleterious effects of Brillouin backscattering, we have inserted an additional phase modulation operated at a low frequency. After the nonlinear propagation, the normal chirp of the pulses is cancelled to a large extend by imprinting a quadratic spectral phase with a programmable spectral filter [5]. By cancelling one spectral component over two or four over five, the same spectral filter can be used to double or quintuple the repetition rate of the pulse train. Results at the different stages are monitored using an optical sampling oscilloscope, an intensity autocorrelator and a high-resolution optical spectrum analyzer.

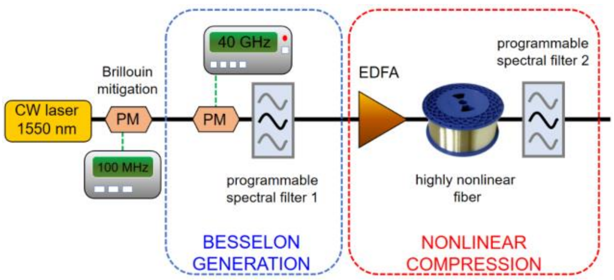

Fig. 1. Experimental setup.

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3 Experimental results

3.1. Results at 40 GHz

The besselon temporal and spectral intensity profiles are plotted in panel (a1) and (b) respectively of Fig. 2. The temporal profile is made of 5.3 ps close to Gaussian pulses without any visible background between two pulses. The temporal intensity profile is in perfect agreement with the analytical waveform of a besselon [4] for an amplitude of the initial phase modulation of 1.3 rad. After the nonlinear propagation, the spectrum of the pulse is significantly broadened and spans over more than 1.6 THz. The nonlinear chirp is partly compensated for by applying a quadratic spectral phase of a 1.12 ps/nm. The pulse train recorded after compression is plotted in panel (c1) and demonstrates that high-quality pulses are generated with a subpicosecond duration. Additional autocorrelation measurements provide a full width duration of 850 fs (based on an assumption of a Gaussian pulse), leading to a duty cycle of 0.034. Panel (c2) recorded in the persistent mode highlights the remarkable stability of the pulse train. The experimental results are in remarkable agreement with the numerical simulations of the process based on the nonlinear Schrodinger equation.

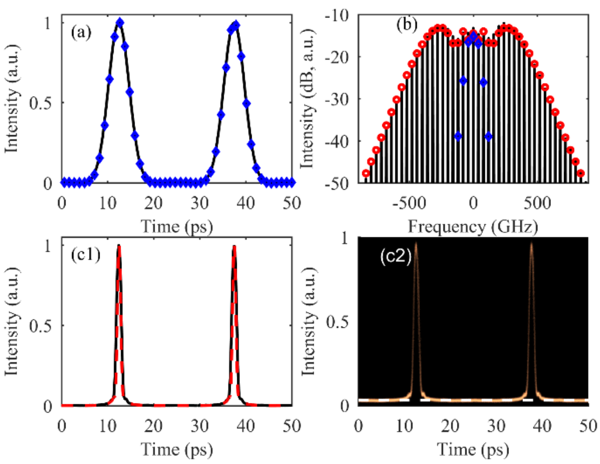

Fig. 2. (a) Temporal intensity profiles recorded on the optical sampling oscilloscope after the first linear shaping (solid line) are compared with the theoretical shape of the besselon (blue diamonds). (b) Optical spectrum after modulation (blue diamonds) and after nonlinear propagation (black lines). Results of numerical simulations are plotted with red circles. (c1) Temporal intensity profiles after the nonlinear propagation and quadratic spectral phase. Results of numerical simulation (red dashed line) are compared with experimental results (black line). Panel (c2) is similar to (c1) but recorded in the persistent mode of the optical sampling oscilloscope.

3.2. Doubling and quintupling of the repetition rate

Doubling and quintupling of the repetition rate is achieved by keeping only one spectral line over two or over five [6]. This processing is achieved thanks to the programmable spectral filter. The resulting spectra are provided in panels (a) of Fig. 3 where can note the excellent optical to noise ratio. The temporal intensity profiles recorded on the optical sampling oscilloscope (panel b and c) confirm the excellent quality of the shaped pulse train. At 80 GHz, the extinction ratio is still remarkable with a duty cycle of 0.09. Measurements made in the persistent mode also confirm the excellent stability of the source. The jitter slightly increases when operating at 200 GHz.

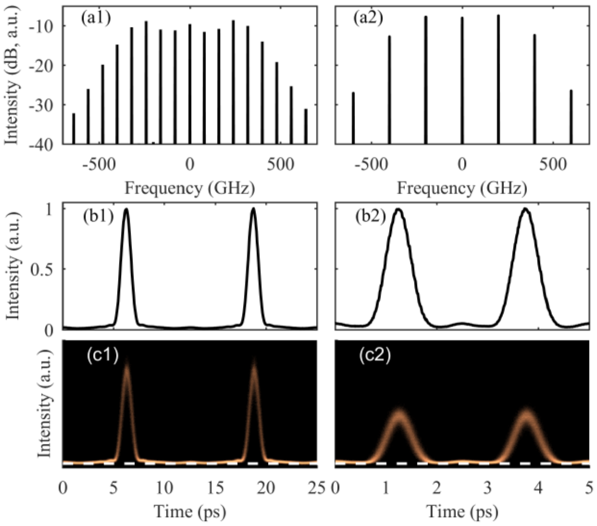

Fig. 3. (a) Spectral and (b) temporal intensity profiles after spectral components cancelation. (c) is the temporal profile recorded in the persistent mode. Panels (1) deal with a repetition rate of 80 GHz whereas panels (2) are obtained at 200 GHz. The white dotted line is the background level of the optical sampling oscilloscope.

To conclude, we have proposed to use the combination of linear and nonlinear compression schemes to achieve subpicosecond pulse trains with a very high quality and duty cycle of 0.034 at 40 GHz. Our approach is simpler than previous multi-stage architectures and only requires an initial phase modulation of 1.3 rad. The use of other operating points that are suitable for clean besselon generation will also be discussed and we will show that is possible to avoid the initial phase modulation used to prevent the Brillouin backscattering.

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