Nonlinear Compression of Besselon Waves for High Repetition-Rate Subpicosecond Pulse Trains

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Abstract—We theoretically and experimentally demonstrate the generation of high-quality low duty-cycle pulse trains at repetition rates of 28 GHz, 56 GHz and 112 GHz. Starting from a continuous wave we benefit from phase modulations in the temporal and spectral domains by applying a sinusoidal profile and a set of well-chosen \( \pi \) shifts, respectively, to generate a train of modified besselons at doubled repetition rate. With further nonlinear spectral expansion in a normally dispersive fiber followed by dispersion compensation we achieve subpicosecond durations and a duty cycle as low as 0.025 at 28 GHz. Spectral cancelation of one component over two or four enables to further double or quadruple the repetition rate.

Index Terms—High repetition-rate sources, subpicosecond pulses, phase modulation, ultrafast processing, nonlinear fiber optics.

I. INTRODUCTION

THE need of picosecond pulses at repetition rates of several tens of GHz has stimulated many fundamental and applied researches in the photonics community. Solutions such as mode-locked fiber lasers have been proposed [1] but remain expensive and require fine tuning of the cavity. Benefiting of the recent progress of high-quality microresonators is another very promising approach: tailoring the frequency comb generated in these microcavities has successfully provided pulse trains at repetition rates from a few tens up to hundreds of GHz. However, the repetition rate of the source is fully determined by the component design and cannot be continuously adjusted. Moreover, the coupling of the initial seed laser with the very narrow resonances of the resonators is still technologically challenging.

As a consequence, cavity-free designs, where pulse train properties directly depend on an external RF modulation, remain an attractive and versatile option. Different schemes are in this context possible. For example, one way is to apply a sinusoidal intensity modulation on a continuous wave laser then followed by a nonlinear compression in one or several segments of fibers [2], [3]. High quality pulse trains are generated but achieving very low duty cycles requires an increasingly complex architecture. A second possible scheme relies on imprinting a temporal sinusoidal phase modulation combined with propagation in a linearly dispersive medium [4], [5]. Ultrashort structures have been demonstrated, but the pulse quality is severely impaired by strong sidelobes or continuous background. Several nonlinear methods, including nonlinear optical loop mirrors [6], additional synchronized amplitude modulation [7] or Mamyshev-like devices [8] have been implemented to get rid of these spurious ripples but once again, they significantly increase the complexity of the setup.

Recently, we have highlighted numerically and experimentally that the results achieved with the second scheme can be significantly improved if the traditionally used quadratic spectral phase is replaced by a triangular one [9]. Fourier-transform limited waveforms are achieved and properly choosing the depth of the initial sinusoidal phase modulation provides an excellent extinction ratio. We named those structures besselons as their main features are governed by the properties of Bessel functions [10]. By applying an additional \( \pi \) phase shift on the central component, we have also demonstrated the generation of a modified besselon that has the advantage of being shorter while keeping an excellent pulse quality. Moreover, it can be time-multiplexed to efficiently double the repetition rate. However, this linear processing only gives structures with a limited duty-cycle of 0.201.

In the present contribution, we combine the modified besselon with nonlinear compression techniques to demonstrate a decrease of the duty cycle by nearly one order of magnitude. Starting from a 14 GHz RF phase modulation, we successfully experimentally demonstrate subpicosecond pulses at repetition rates up to 112 GHz.

II. PRINCIPLE OF OPERATION

The principle of our proposed architecture is illustrated in Fig. 1. Starting from continuous wave (CW) which phase has been modulated in the temporal domain by a sinusoidal profile with a depth of modulation \( \Delta m \) and an angular frequency \( \omega_m \), we apply a triangular spectral profile made of \( \pi/2 \) discrete phase shifts combined with an additional central \( \pi \) phase shift (refer to the blue line in Fig. 2(b)). Such a processing leads to the generation of a coherent structure we named optical modified besselon. In ref [10], we provided an in-depth analytical analysis of this new waveform which temporal profile is analytically expressed as (for \( \Delta m > 2.4 \text{ rad} \)):

\[
\psi_B(t) = -J_0(\Delta m) + 2 \sum_{n=1}^{\infty} J_n(\Delta m) \cos(n \omega_m t)
\]  

where \( J_n \) are the Bessel functions of the first kind of order \( n \). The resulting temporal intensity profile (see panel (a1) in Fig. 1) highlights that the initial phase modulated signal reshapes into a train of short structures at the repetition
Fig. 1. Numerical simulation of the evolution of the (a) temporal and (b) spectral properties of the shaped signal at different stages. Full and black dashed lines are used for the intensity profiles and the phase profiles, respectively. Modified besselon arising from the sinusoidal phase modulation with a depth of $A_m = 3.72$ rad and frequency 14 GHz followed by the spectral phase cancelation is depicted in panels (1). Panels (2) display profiles at the doubled repetition rate of 28 GHz after cancellation of the odd spectral components. The properties of the wave after the nonlinear propagation before and after applying a quadratic spectral phase are shown in panels (3) and (4), respectively. Inset of Fig. 4(a) is a magnification of the central part of the pulse, which is compared to a Gaussian fit (dashed red). Panels (5) show a case of further doubling of the repetition rate reaching 56 GHz. The dashed red line is the intensity profile plotted on a logarithmic scale.

rate $\omega_m$. However, the pulses are impaired by strong side-lobes and high background. Interestingly, we have shown in ref. [10] that a very efficient way to get rid of these spurious ripples while doubling the repetition rate is to cancel the odd frequency components of spectrum. The resulting field is:

$$\psi_B^2(t) = \cos(A_m \sin(\omega_m t)) - 2 J_0(A_m).$$

and presents a duty cycle of 0.201 with an optimum signal extinction ratio obtained for $A_m = 3.72$ rad.

In order to further decrease the pulse duration, we benefit from nonlinear spectral expansion by combining the initial linear besselon generation stage with propagation in a highly nonlinear fiber (HNLF). In contrast to soliton-like compression [11] or to Mamyshev-like schemes [8], we have found that compression based on normally dispersive fibers [12] leads to the best performance in terms of pulse quality (level of resulting sidelobes, extinction ratio, symmetry). We consider here propagation in a HNLF with parameters corresponding to the experimental demonstration described in the next section: nonlinear coefficient $\gamma$ of 10 W/km, second order dispersion coefficient $\beta_2$ of 0.89 ps$^2$/km, attenuation of 0.5 dB/km. The evolution of light in the HNLF can be predicted using the well-known nonlinear Schrodinger equation solved by the split-step Fourier algorithm. We notice in panel (b3) that, for an average input power of 27 dBm, the spectrum has been significantly expanded to reach a width of 1.4 THz. Oscillations of the spectrum are rather moderate. Combination of Kerr nonlinearity with normal dispersion leads in the temporal domain to the reshaping of the besselon pulses towards a parabolic like structure having a parabolic phase. The pulses have broadened and care should be devoted to avoid overlapping of the neighboring structures. This may in practice limit the repetition rate when involving initial RF frequencies well above 20 GHz. Temporal compression of the parabolic structures is achieved by applying a quadratic spectral phase [12]. The resulting profiles (panel (a4)) stress the quality of the resulting pulse train. Durations as short as 0.95 ps are achieved, leading to a duty cycle as low as 0.027. Quite remarkably, an excellent extinction ratio is maintained and no spurious sidelobes are visible. Consequently, it is possible to temporally interleave those pulses to further increase the repetition rate. For example, suppressing one frequency component over two leads to the results plotted in panel (a5) with an excellent quality maintained. An alternative technological solution could be the use of the fractional Talbot effect [13].

III. Experimental Setup

The experimental setup we implemented is sketched in Fig. 2(a) and is based on devices typical of the telecommunication industry. The number of optical elements is voluntarily limited. An initial CW at 1550 nm is delivered by an external cavity laser. In order to generate the modified besselon, the temporal phase of the CW is modulated by a sinusoidal RF signal delivered by an electrical clock running at a frequency...
of 14 GHz. The modulation depth of 3.72 rad which is required to
generate the optimum waveform is achieved thanks to a
low-Vπ LiNbO3 phase modulator (PM). The spectral
phase is then sculptured using a linear spectral shaper [14].
To double the repetition rate and to simultaneously make
the waveform Fourier transform limited, we use the phase
only spectral mask (red line in Fig. 2(b)). Rather than using
the direct programming amplitude attenuation, which would
have been strongly impacted by the resolution of our shaper,
we have replaced two successive π/2 phase shifts by a single
π phase shift imprinted exactly on the odd components. Due to
the intrinsic limitations of the shaping process, this π phase
jump induces a notch filter [15] as confirmed by the level
of transmission of an amplified spontaneous emission (black
line) that exhibits a narrow bandwidth attenuation higher than
20 dB. Note that given the already very low amplitude of the
harmonics at ±14 GHz, we have not tried to further cancel
them.

The frequency doubled signal is then amplified by an
erbium-doped fiber amplifier (EDFA) that delivers up to
27 dBm of average power. The nonlinear spectral expansion
takes place in a normally dispersive HNLF with properties
reported in the previous section. The high level of initial
phase modulation enables us to avoid the deleterious effects
of Brillouin backscattering. Contrary to other cavity-free schemes
based on nonlinear sculpturing, it is therefore not required to
insert an additional phase modulator aimed at Brillouin mitiga-
tion that could induce some additional jitter [3]. At the output
of the nonlinear fiber, a second programmable filter is used to
compensate the chirp of the signal by imprinting a quadratic
spectral phase [14] (see spectral profile in Fig. 2(c1)). Note
that such phase compensation could also have been achieved
using fiber Bragg gratings or a simple piece of anomalous
fiber operating in the linear regime of propagation. The
spectral shaper also enables us to increase the repetition
rate by canceling one component over two or over four on the
nonlinearly broadened spectrum (see transmission masks in
Fig. 2(c2-3)). Imprinting attenuation helps remove partly
the amplified spontaneous emission introduced by the EDFA.

The detection of the temporal properties of the shaped
pulses has been achieved thanks to an optical sampling oscil-
loscope (OSO). For the measurement of temporal durations
below the resolution of the OSO (1 ps), we also involved an
autocorrelator based on second-harmonic generation. Spectral
properties are recorded on a high-resolution optical spectrum
analyzer that was also used for the fine adjustment of the linear
shaper.

IV. EXPERIMENTAL VALIDATION
A. Generation of Pulse Trains at 14 and 28 GHz

The experimental results achieved for a repetition rate
of 14 and 28 GHz are summarized in Fig. 3. After the
stage of initial temporal phase modulation and spectral phase
cancelation (panels 1), the temporal and spectral intensity
profiles are found in perfect agreement with the analytical
predictions based on Eq. (1). The phase modulation made
of discrete π phase shifts efficiently kills the odd spectral
components and increases the repetition rate up to 28 GHz
where the experimental temporal and spectral properties are
once again found in excellent agreement with the theoretical
predictions of Eq. (2). The FWHM duration of the resulting
pulses is 7.2 ps, leading to a duty cycle of 0.2. Panel (b3)
highlights the nonlinear signal expansion occurring in the
HNLF for an input average power of 27 dBm. The spec-
trum has broadened symmetrically and presents a width at
-20dB that has been increased by a factor 6.25 and becomes
larger than 1.4 THz. The temporal duration has increased up to
9.2 ps. The combination of normal dispersion and Kerr
nonlinearity has led to the expected parabolic-like temporal
intensity profile [3]. A parabolic spectral phase applied on the
second programmable filter compresses the pulse down to the
picosecond level while maintaining a profile that is free from
pronounced sidelobes. The pulse train measured on the optical
sampling oscilloscope is plotted on panel (a4). It has a duration
of 1.12 ps that is comparable with the resolution of the device
and confirms an excellent extinction ratio (higher than 20 dB,
see inset (a4)). Measurements made in the persistent mode are

![Figure 3](image-url)
provided on top of the panel (a4) and stress the high stability of the pulse train. In order not to be impaired by the temporal resolution of the OSO, we also recorded the autocorrelation signal. Results are plotted in panel (c) and confirm the absence of significant pedestals. Comparison between the experimental recordings and a Fourier transform limited waveform derived from the optical spectrum highlights that the quadratic phase compensation has led to a nearly ideal waveform. Fitting with a Gaussian waveform gives a temporal duration close to 0.89 ps, leading to a duty-cycle of 0.025.

B. Generation of Pulse Train at 56 and 112 GHz

Experimental results achieved when further doubling or quadrupling the repetition rate are summarized in Fig. 4. The various spectra (panels a) highlight the efficient suppression of one component over 2 or 4 while maintaining a high OSNR (higher than 40 dB when measured on a 5 MHz bandwidth). The temporal intensity profiles measured on the OSA confirm that a high quality is maintained. Measurements made with the autocorrelator provide a FWHM duration of 0.88 ps and 1 ps (with the Gaussian assumption), leading to duty cycles of 0.05 and 0.11 respectively. The temporal measurements reveal that some bumps appear between the pulses when quadrupling the repetition rate. Such small bumps are attributed to the constructive interference between the wings of two adjacent pulses. They are reproduced by numerical simulations and indicate that higher repetition rates will be difficult to achieve.

V. CONCLUSION

By using the nonlinear compression of modified besselon pulses, we have demonstrated the generation of sub-picosecond high quality pulses using a simple experimental architecture. Starting from an RF signal at 14 GHz to target applications to the telecommunication industry, the combination of linear and nonlinear fiber-based processing has enabled to obtain high quality pulse trains with a duty cycle as low as 0.025 at 28 GHz. As the architecture is cavity-free, the repetition rate is fully tunable as long as the spectral shaping stage is efficient. Compared to the cavity-free solutions previously reported [3], [6]–[8], [13], a single phase modulator is here required, less segments of fibers are involved and the absence of Brillouin backscattering avoids the implementation of a dithering modulation.

ACKNOWLEDGMENT

The authors acknowledge the support of the Institut Universitaire de France (IUF), the Bourgogne-Franche Comté Region. The experiments have benefited from the PICASSO experimental platform of the University of Burgundy. They thank B. Kibler and S. Boscolo for fruitful discussions as well as U. Andral for initial developments of the Besselon experimental concept.

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Fig. 4. Properties of the signal after additional doubling and quadrupling of the repetition rate reaching 56 and 112 GHz are displayed in panels (1) and (2), respectively. (a) Optical spectra. (b) Temporal intensity profiles recorded on the optical sampling oscilloscopes. Red dots and red dashed lines are for the results of numerical simulations. (c) Autocorrelation signals (black) fitted by the autocorrelation of a Gaussian (blue).