High-quality 10 and 20 GHz repetition rate optical sources based on the spectral phase tailoring of a temporal sinusoidal phase modulation

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ABSTRACT
We theoretically introduce and experimentally demonstrate a new approach to generate high-quality, high repetition-rate pulse trains. This method is based on a temporal sinusoidal phase modulation combined with a triangular spectral phase shaping. Experimental results validate the concept at repetition rates of 10 and 20 GHz.
Keywords: High repetition-rate optical sources, optical processing, phase modulation.

1. INTRODUCTION

Temporal sinusoidal waveform is the pattern that is the most easily generated by an oscillator. It can be used to modulate the phase of a continuous wave or a pulsed signal and several applications have highlighted various benefits of involving such modulation in the context of pulse compression [1], of spectral compression enhancement [2], of wavelength conversion [3], of mitigation of unwanted self-phase modulation [4], of optical sampling [5] or of improvement of a moderate extinction ratio [6]. However, one of the most exciting and practical applications of phase modulation is its use in conjunction with a dispersive element. Indeed, the temporal sinusoidal phase modulation combined with a quadratic spectral phase has led to the efficient generation of picosecond pulses at repetition rates of 10 GHz or above [7, 8].

However, this technics suffers from a limited extinction ratio for the resulting pulse train with strong unwanted background or sidelobes being present between two successive pulses [9]. We introduce theoretically an alternative scheme where the quadratic spectral phase is replaced by a triangular one. Fourier-transform limited structures can be obtained. Experimental validation carried out at 10 and 20 GHz confirm that high-quality close-to-Gaussian pulse trains can be achieved with an excellent extinction ratio and with a duty cycle below 1/4, in full agreement with the numerical simulations.

2. PRINCIPLE OF OPERATION

In order to illustrate our approach, let us first consider a continuous optical wave ψ_0 which phase is temporally modulated by a sinusoidal waveform:

$$\psi(t) = \psi_0 \; e^{i A_m \cos(2\pi f_m t)},$$

where A_m is the amplitude of the phase modulation and f_m its frequency. We have plotted on Fig. 1 the resulting phase and intensity profiles both in the temporal and spectral domains for A_m = 1.1 rad and f_m = 20 GHz. The temporal sinusoidal phase leads to a set of spectral lines that are equally spaced by f_m and which amplitude can be derived using a Jacobi-Anger expansion [10]:

$$\psi(t) = \psi_0 \sum_{n=-\infty}^{\infty} i^n \; J_n(A_m) \; e^{i 2\pi n f_m t}$$

Therefore, the n^{th} spectral component has an intensity proportional to J_n^2, with J_n being the Bessel function of the first kind of order n. An essential point that has not been stressed and exploited in the previous works is the existence of a phase shift of $\pi/2$ between each spectral component (Fig. 1(b1)). These equally spaced spectral phase shifts can also be described by a triangular spectral phase profile. Involving a dispersive effect, i.e. applying a quadratic spectral phase, cannot fully compensate for this phase profile, leading to a deleterious residual background and a poor extinction ratio. With the progress of linear shaping, it has become now feasible to imprint a triangular spectral phase profile of opposite sign. Therefore, for A_m < 2.40 rad, a flat spectral phase can be achieved, leading to a Fourier-transform limited waveform that can be expressed as:

$$\psi(t) = \psi_0 \sum_{n=-\infty}^{\infty} J_{|n|}(A_m) \; e^{i 2\pi n f_m t}$$

As a consequence, in the temporal domain, the initial continuous wave is strongly reshaped into a train of well-separated ultrashort pulses at the repetition rate f_m (Fig. 1(a2)).

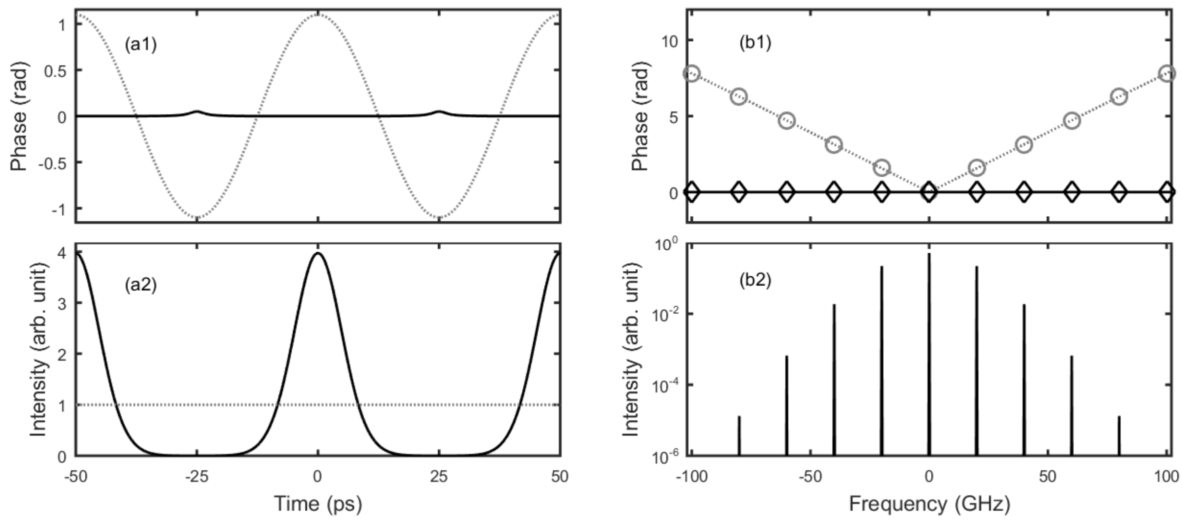

Figure 1. Principle of the source: (a) temporal and (b) spectral properties of the modulated waveform for an initial amplitude modulation A_m of 1.1 rad. The initial phase modulated signal is plotted with grey lines. The results obtained after spectral phase processing is plotted with solid black lines.

Figure 2 presents the influence of the phase modulation amplitude A_m on the resulting waveform. Higher A_m is, shorter are the generated pulses with an increased peak power. However, the extinction ratio of the pulse train does not evolve monotonously and a value around A_m = 1.1 rad clearly leads to the lowest level of residual background. For this operating point, the pulses have theoretically a full width at half maximum (fwhm) duration of 12 ps and an extinction ratio of well above 20 dB.

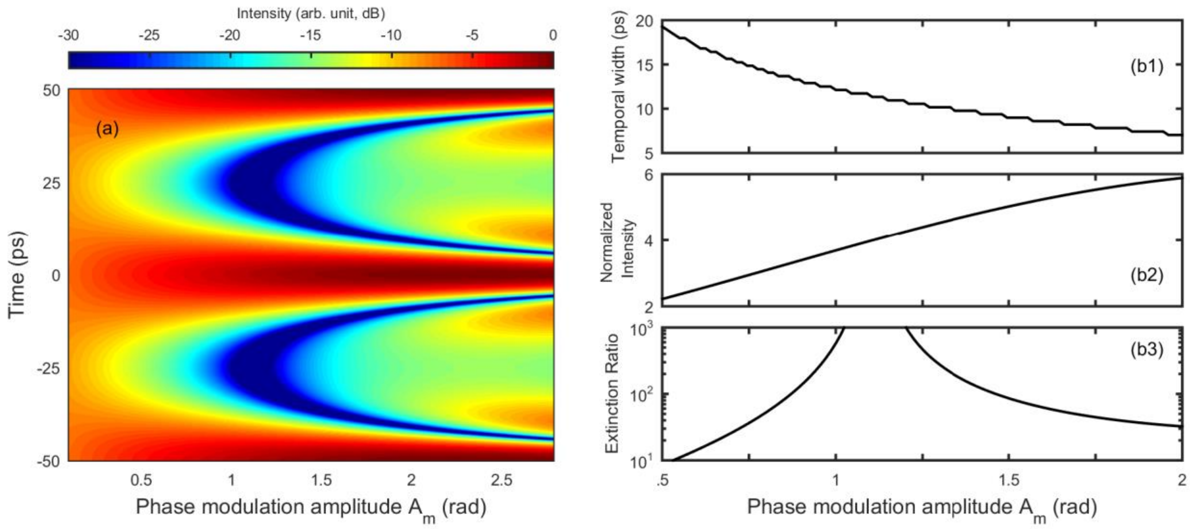

Figure 2. Impact of the phase modulation amplitude A_m. (a) Evolution of the temporal intensity profile. (b) Evolutions of the fwhm temporal width, of the peak temporal intensity and of the extinction ratio are plotted in panels 1, 2 and 3, respectively.

3. EXPERIMENTAL VALIDATION

The experimental setup is sketched on Fig. 3 and is based on devices that are commercially available. A continuous wave laser at 1550 nm is first temporally phase modulated using a Lithium Niobate device driven by a sinusoidal electrical signal. A linear spectral shaper (Finisar Waveshaper) is then used to apply the triangular spectral phase that we want to test. Note that for repetition rates above 10 GHz, it is also possible to apply discrete spectral phase shifts of $\pi/2$ between two successive components. The resulting signal is recorded on a high-speed optical sampling oscilloscope (1 ps resolution) and with a high-resolution optical spectrum analyzer.

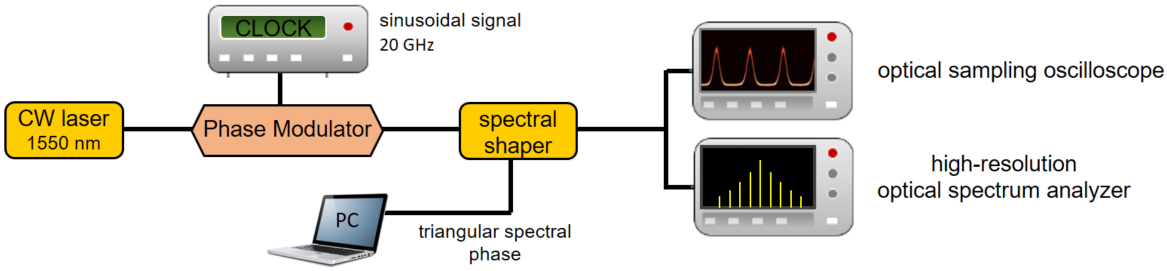

Figure 3. Experimental setup

Evolution of the temporal intensity profile according to the average electrical power applied to the phase modulator is summarized in Fig. 4(a). These results obtained for f_m = 10 GHz confirm that the achievement of a significant extinction ratio requires to carefully choose A_m and the experimental trends are similar to the one reported on Fig. 2(a): for low modulations, a continuous background remains between two pulses whereas for excessive modulations, an unwanted bounce emerge. For optimum modulation, the pulses have a fwhm duration of 21 ps.

Results obtained at a frequency of 20 GHz are plotted on panels 2 of Fig. 4. Once again, highly-stable pulses with an excellent extinction ratio (> 20 dB) are recorded with a fwhm temporal duration of 12 ps that is fully in line with the numerical predictions. The temporal intensity profile of the pulse can be closely approximated by a Gaussian waveform. High resolution optical spectra shown in panels (c) outline the quality of the signal with an optical signal to noise ratio above 60 dB (measured here with a resolution of 5 MHz). The pulse train is found to be experimentally Fourier-transform limited.

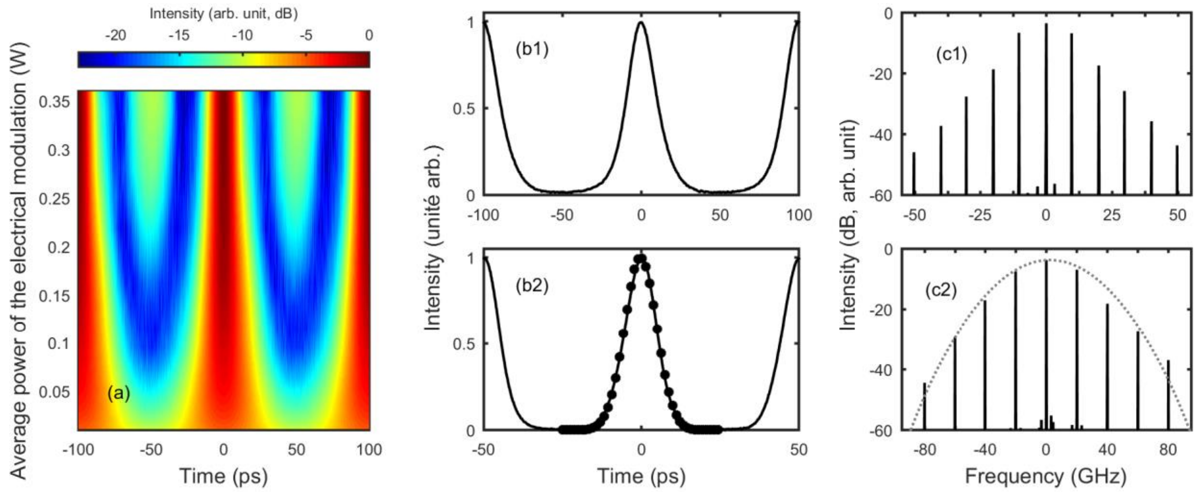

Figure 4. Experimental results. (a) Evolution of the temporal intensity profile according to the average electrical power applied to the phase modulator for a frequency modulation of 10 GHz. Evolution of the (b) temporal and (c) spectral intensity profiles, at the point of optimal compression at a repetition rate of 10 and 20 GHz (panels 1 and 2 respectively). Experimental results (solid lines) are compared with a Fourier-transform limited Gaussian waveform (black circles and dotted grey line).

CONLUSION

We have theoretically and experimentally demonstrated that a sinusoidal temporal phase modulation followed by a simple triangular spectral phase makes it possible to efficiently generate high-repetition rate pulse trains. Optimum extinction ratio is achieved for a phase modulation of 1.1 rad for which the resulting pulses are extremely close to a Gaussian shape and are Fourier-transform limited. Experiments achieved at 10 and 20 GHz fully confirm the theoretical analysis. We will also discuss some preliminary experimental results obtained at higher repetition rates (30 and 40 GHz) that validate the versatility of the technics. Finally, combined with additional non-linear techniques, the duty-cycle can be reduced [11, 12].

ACKNOWLEDGEMENTS

We acknowledge financial support by the Région Bourgogne-Franche Comté (Pari Photcom) and the Agence Nationale de la Recherche (Labex Action ANR-11-LABX-01-01). This work was also supported by the European Union within the framework of the operational Program FEDER-FSE Bourgogne 2014-2020 and by the Institut Universitaire de France.

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