Triangular spectral phase tailoring for the generation of high-quality picosecond pulse trains

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We theoretically and experimentally demonstrate a new electro-optic linear approach to generate high-repetition-rate picosecond pulse trains. This simple cavity-free method is based on a temporal sinusoidal phase modulation combined with a triangular spectral phase processing. Experimental results validate the concept at repetition rates ranging from 10 GHz up to 40 GHz with the generation of background-free pulse trains made of nearly Gaussian Fourier-transform-limited pulses. © 2019 Optical Society of America

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The generation of high-quality pulse trains at repetition rates of several tens of GHz remains a crucial step for optical telecommunications, optical sampling, or component testing applications. Unfortunately, the current bandwidth limitations of optoelectronic devices does not allow the direct generation of well-defined optical pulse trains with low duty cycles. Actively mode-locked fiber lasers were found to be an efficient way to overcome this limitation [1], but they remain an onerous and complex option. As an alternative approach to conventional mode-locking operation, several cavity-free operation techniques have been suggested, such as the nonlinear reshaping of a sinusoidal beating into a train of well-defined, pedestal-free pulses [2]. For example, taking advantage of the distributed interaction of the anomalous dispersion of an optical fiber with its Kerr nonlinearity, multiple four-wave mixing has enabled the generation of Fourier-transform-limited pulses at repetition rates exceeding 1 THz [3]. The concatenation of dispersion-managed segments of fibers [4] is another solution that may benefit from the nonlinearity of optical fibers.

An alternative set of linear solutions is based on a direct temporal phase modulation that is then converted into an intensity modulation. Such a conversion can be achieved using two different schemes. One relies on the use of a frequency-shifted optical bandpass filter [5,6]. This simple technique is efficient to produce ultrashort pulses but is intrinsically highly dissipative. A second well-known approach is based on a dispersive element that imprints a spectral quadratic phase. Picosecond pulses at repetition rates of several tens of GHz have been successfully demonstrated [7,8]. Taking advantage of the space/time duality of dispersion, an analogy with a lenticular lens [9] or with a Fresnel diffraction pattern by a pure phase grating can be drawn. However, this approach suffers from a limited extinction ratio or from the presence of detrimental temporal sidelobes [10], so that a considerable part of the energy lies outside the main pulses. In order to reject these residual background and tails, various architectures have been proposed, such as the use of a broadband optical carrier [11], of a nonlinear optical loop mirror [12], or of an additional amplitude modulation with optical bandpass spectral filtering [13,14].

We introduce here theoretically and experimentally an alternative scheme where the quadratic spectral phase is replaced by a triangular one. With such a specific phase processing, Fourier-transform-limited structures are obtained. Experimental validation carried at repetition rates between 10 and 40 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 our numerical simulations and theoretical predictions.

In order to illustrate our approach, let us first consider a continuous optical wave with an amplitude \( \psi_0 \) and a carrier frequency \( f_c \), \( \Psi(t) = \psi_0 \psi(t) e^{i2\pi f_c t} \), whose phase is temporally modulated by a sinusoidal waveform,

\[
\psi(t) = e^{iA_m \cos(2\pi f_m t)},
\]

where \( A_m \) is the amplitude of the phase modulation and \( f_m \) is its frequency. We have reported in Fig. 1 the resulting phase and intensity profiles both in the temporal and spectral domains for \( A_m = 1.1 \) rad. The temporal sinusoidal phase leads to a set of spectral lines that are equally spaced by \( f_m \) and whose amplitude can be expressed using a Jacobi–Anger expansion [15],

\[
\psi(t) = \sum_{n=-\infty}^{\infty} i^n f_n(A_m) e^{i2\pi n f_m t}.
\]

Therefore, the \( n \)th spectral component has an intensity proportional to \( f_n^2 \), with \( f_n \) being the Bessel function of the first kind of order \( n \). An essential point that has not been stressed and exploited so far is the existence of a phase shift of \( \pi/2 \) between each spectral component [see cyan line in Fig. 1(b1)].
Consequently, these equally spaced spectral phase shifts can also be described by a triangular spectral phase profile. Involving a purely dispersive element, i.e., applying a quadratic spectral phase, one can partly compensate for this initial phase, leading to the emergence of temporally localized pulse structures with a period $T_0 = 1/f_m$. Since the spectral phase is not perfectly canceled, a deleterious residual background and a poor extinction ratio can be observed on the resulting intensity profile [Figs. 1(a1) and 1(a2)], as well as an uncompensated residual temporal phase. However, with the progress of linear shaping, one can now process a line-by-line spectral phase profile using liquid crystal modulators [16] or fiber Bragg gratings [17]. It then becomes feasible to imprint an exact 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 $\psi(t)$ that can be expressed as

$$\psi(t) = j_0(A_m) + 2 \sum_{n=1}^{\infty} j_n(A_m) \cos(2\pi nf_m t).$$

As a consequence, in the temporal domain, the initial phase modulation is converted into a pure intensity modulation leading to a train of well-separated ultrashort pulses at the repetition rate $f_m$ [Figs. 1(a2) and 1(a3)]. It should be also noted that for $A_m = 1.1$ rad, the resulting intensity profile can be closely adjusted by a Fourier-transform-limited Gaussian shape [see blue full circles in Figs. 1(a3) and 1(b3)]. Finally, the resulting pulse train has a duty cycle of 1/5 and is characterized by an excellent extinction ratio (values above 30 dB are achieved, the extinction ratio being defined as the ratio of the peak power by the minimum intensity of the pulse value) well beyond the performance, which can be achieved with a usual group delay dispersion circuits imprinting a quadratic spectral phase.

Figure 2 illustrates the influence of the phase modulation amplitude $A_m$ on the resulting waveform and according to the spectral compensation scheme. The higher $A_m$ is, the shorter the generated pulses with an increasing peak power. Whereas triangular or parabolic spectral phase leads to rather similar results in terms of temporal duration [Fig. 2(b1)], the resulting peak power [Fig. 2(b2)] is enhanced with the triangular scheme due to a reduced amount of energy remaining in the residual sidelobes or background. Therefore, the extinction ratio is dramatically improved for a triangular phase shaping as can be noticed in Fig. 2(a). While quadratic phase spectral compensation cannot enable an extinction ratio well above 10, results are improved by more than 1 order of magnitude when the triangular spectral phase is applied for $A_m$ between 1 rad and 1.25 rad. Moreover, extinction ratios above 20 dB can be expected with an optimum value obtained for $A_m = 1.1$ rad. However, for higher modulation depth of the
phase, a residual background or sidelobes appear so that it is impossible to achieve outstanding extinction ratios with duty cycles above 1/6.

The experimental setup is sketched in Fig. 3 and is based on devices that are commercially available and typical of the telecommunication industry. A continuous wave (CW) laser at 1550 nm is first temporally phase modulated using a lithium niobate electro-optic device driven by an amplified sinusoidal electrical signal. A linear spectral shaper (Finisar Waveshaper) based on liquid crystal on silicon technology [18] is then used to apply the suitable triangular spectral phase under test. Using such a programmable filter enables us to accommodate a large set of repetition rates. Note that for repetition rates above 10 GHz, given the shaper properties, it becomes also possible to replace this triangular profile by a set of simple discrete spectral phase shifts of $\pi/2$ applied between two successive components. Therefore, for operation at a fixed wavelength and a fixed repetition rate, the linear shaping stage can be fully realized by a cascaded uniform fiber Bragg grating [17]. In order to ensure enhanced environmental stability, polarization-maintaining components have been used. Moreover, since the principle of operation is purely linear, no erbium-doped fiber amplifier is required, thus limiting the source of detrimental noise. The reshaping process is here quite energy efficient, since the optical losses are restricted to the insertion losses of the phase modulator and of the spectral shaper. The resulting signal is directly recorded by means of a high-speed optical sampling oscilloscope (1 ps resolution) and with a high-resolution optical spectrum analyzer.

Experimental evolution of the temporal intensity profile according to the amplitude of the phase modulation 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 $A_m$, typically between 1 and 1.25 rad. The experimental trends are similar to the numerical predictions depicted in Fig. 2(a1): for low modulations, a continuous background remains between two consecutive pulses, whereas excessive modulations induce unwanted bounces. Positions of the minima of the temporal intensity profile are also fully in line with the numerical simulations (white dotted line). For an optimum phase modulation depth ($A_m = 1.1$ rad), the pulses are characterized by a FWHM duration of 21 ps, and the resulting temporal intensity profile [Fig. 4(b)] matches perfectly the analytical results of Eq. (3) with a summation truncated to the first three harmonic terms. This indicates that in practice, the phase shaping of entire spectrum is not a mandatory requirement and that nice waveforms can already be expected by manipulating a few central spectral components.

Details of the pulse train obtained for $f_{m} = 20$ GHz and for the optimum phase modulation $A_m = 1.1$ rad are provided in Fig. 5. Once again, pulses with an excellent extinction ratio (>20 dB) are recorded with a FWHM temporal duration of 12 ps in line with the numerical predictions. Figure 5(a) stresses the high level of stability of the pulse train with negligible temporal or amplitude jitter. Indeed, in contrast to nonlinear reshaping schemes that may suffer from severe Brillouin backscattering in fiber segments under test, it is not here required to involve additional phase modulation that may turn
into detrimental jitters [19]. The temporal intensity profile of the pulse can be closely approximated by a Gaussian waveform [Fig. 5(b)] and its spectrum corresponds to the Fourier transform limit (dotted blue line). High-resolution optical spectra [Fig. 5(c)] outline the quality of the resulting signal with an optical signal to noise ratio above 60 dB (measured with a resolution of 5 MHz).

Finally, we have also tested the capacity of our experimental setup to generate higher-repetition-rate pulse trains. Results obtained for \( f_m = 30 \) and 40 GHz are plotted in Figs. 6(a) and 6(b), respectively. Temporal durations of 7.5 and 6.8 ps have been recorded, leading to duty cycles of 0.22 and 0.27, respectively. The slightly degraded results at 40 GHz are mainly explained by the bandwidth limitations of our phase modulator that lead to a decrease of the amplitude of the phase modulation that can in practice be imprinted at high frequencies (\( A_m \) is indeed limited to 1 rad at 40 GHz). Results plotted on a logarithmic scale [Figs. 6(a2) and 6(b2)] outline that the floor level is close to \(-20\) dB and is limited by the measurement capabilities of our temporal optical detection. This confirms the excellent extinction ratio achieved at both repetition rates. Once again, the temporal intensity profiles exhibit an excellent pulse quality: no sidelobes are observed, and the profiles are closely adjusted by a Gaussian waveform [blue full circles in Figs. 6(a2) and 6(b2)].

To conclude, we have theoretically and experimentally demonstrated the generation of high-repetition-rate trains of ultrafast pulses from the periodic modulation of the phase of a CW laser source. The key ingredient to achieve high-quality pulses is the perfect phase compensation process provided by a simple triangular spectral phase profile. Optimum extinction ratio is obtained for a phase modulation of 1.1 rad for which the resulting pulses are extremely close to a Fourier-transform-limited Gaussian shape. Experimental demonstrations carried out at repetition rates ranging from 10 GHz up to 40 GHz fully confirm the theoretical analysis as well as the versatility of this novel technique. Since the present architecture does not involve long pieces of fiber or nonlinear effects, highly stable operation over hours has been recorded without any significant deviations. The experimental demonstration has been achieved at 1550 nm, but the method can be straightforwardly adapted to any other wavelength where high-speed phase modulators are available. As the process is linear, we can also expect that several channels could be efficiently processed simultaneously. Finally, combined with additional nonlinear reshaping techniques, it is expected that the duty cycle can be further reduced [4,19,20], and pulses of only a few picoseconds should be achieved.

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