Phase-only synthesis of ultrafast stretched square pulses

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Abstract: We report the generation of square temporal-shape pulses with no loss of spectral bandwidth, using an analytic expression for the spectral phase modulation dependent only on the input spectrum and stretching factor. We demonstrate numerically and experimentally conversion of 40fs pulses into 150 times longer flat top pulses with sharp on and off fronts. Applications in pulse amplification and free electron lasers are considered.

OCIS codes: (320.5540) Pulse shaping; (050.1590) Chirping; (320.7100) Ultrafast measurements.

References and links

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1. Introduction

Energy scaling of ultrafast lasers is limited by the self-action of the electromagnetic field propagating through optical media, manifested as self-phase modulation (SPM) or self-focusing, limits the peak intensity that can be transmitted. When the light pulses are ultrashort ($< 10^{-12}$ s), the threshold for self-action is reached with very low energies. The introduction of chirped pulse amplification (CPA) and later optical parametric CPA (OPCPA) were significant steps in the scaling of ultrafast laser pulse [1–4]. The lower peak intensity of the square pulses implies a higher gain that a CPA system can sustain without damage. We present a method of stretching a pulse with arbitrary spectrum to generate a square pulse in time using nonlinear spectral phase modulation. Beyond self-action mitigation flat top pulses are desirable for multiple applications from free electron lasers to endoscopy. Generation of square pulses using spectral phase modulation, as presented here, is advantageous because the pulses can be recompressed to their original duration by applying the inverse spectral phase.

The chirp process stretches all frequency components equally by an amount limited only by the gratings used [5,6]. It becomes evident in Fig. 1 that for a Gaussian pulse, the peak of the pulse is near the self-action threshold but the rest of the pulse is well below the threshold. Clearly, a different pulse shape would be able to satisfy the condition of maintaining peak intensity below the threshold while occupying a smaller temporal footprint. When the stated goal is to minimize pulse duration while not exceeding the self-action threshold, the optimum solution is a square (flat top) pulse, as illustrated in Fig. 1. Note the square pulse with the same full-width at half maximum (FWHM) as the Gaussian is three times shorter than the Gaussian pulse T_{Gauss}. The discussion here is relevant to ultrafast laser pulses; therefore, the square pulse must maintain the entire spectral bandwidth of the original pulse. Only such pulses can be re-compressed to their original pulse duration by introducing the inverse phase used to create them. Here we show how such square pulses can be created starting from laser pulses with any spectral shape.

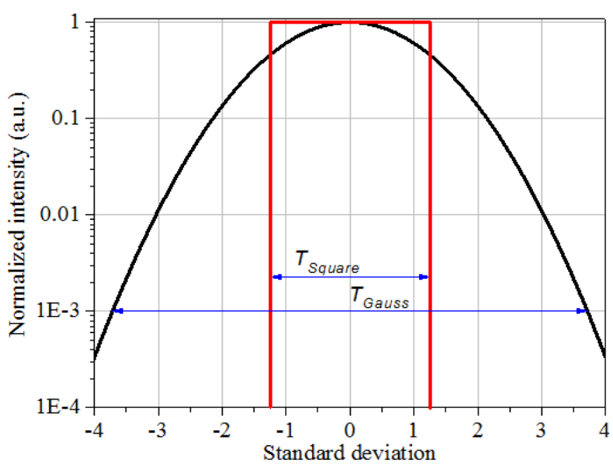

Fig. 1. Simulated intensity of a Gaussian (black) and square (red) pulses with equal peak power and FWHM as a function of time in units of Gaussian standard deviation. T_{Square} and T_{Gauss} are the bottom-to-bottom pulse durations for square and Gaussian pulses, respectively.

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A number of approaches have been explored for the generation of square pulses starting with femtosecond pulses. The first approach uses a pulse shaper that introduces a phase and amplitude mask in the frequency domain that corresponds to the Fourier transform of the square pulse in the time domain. This method was implemented using a microlithograhically etched mask [7] and later using a liquid crystal spatial light modulator [8]. The main drawback to this approach is the resulting spectral narrowing caused by the amplitude mask. This approach could not provide a viable alternative for CPA because of irreversible pulse broadening in the time domain. Second, flat top 200fs FWHM pulses were created using a phase mask that was found using both a genetic algorithm and a Gerchberg-Saxton algorithm [9]. This approach works; however, for every input laser spectrum and final square pulse duration the phase needs to be determined by the optimization algorithm. Third, an approach, which limits the spectral bandwidth with a super-Gaussian spectrum and an optimally designed phase was explored numerically but has not been implemented experimentally [10]. Finally, there is an intriguing approach that is based on the concept of stacking pulse replica one after the other in order to create a flattop pulse with pulse duration equal to the number of pulses stacked in time [11]. The advantage of this method is its simplicity. The disadvantage is that spectral interference among the replicas results in the sync-function spectrum of the output square pulse, which is much narrower than the input pulse spectrum.

2. Theoretical concept

The phase-only generation of a stretched square pulse is based on the following concept. In the limit of large linear chirp the temporal shape of a stretched pulse approaches its spectral intensity $I(\omega)$. In this case the delay $\tau(\omega) = d\varphi(\omega)/d\omega$ is a linear function, and its derivative, i.e. local stretching $d\tau(\omega)/d\omega = d\varphi(\omega)^2/d\omega^2$, is a constant. Therefore all frequency components are linearly delayed or advanced and stretched equally such that the spectral shape is mapped to the pulse shape. Consider a pulse with a Gaussian spectrum. Linear chirp stretches the pulse and its shape remains Gaussian (see Figs. 2(a) and 2(b)). To make a square pulse one has to adjust the local stretching $d\tau(\omega)/d\omega$ to account for changes in spectral intensity: higher intensity requires more stretching, lower intensity—near the wings—requires less stretching (see Figs. 2(c) and (d)). Therefore $d\tau(\omega)/d\omega$ is proportional to the spectral intensity $I(\omega)$ of the pulse

$$\frac{d\tau(\omega)}{d\omega} \equiv \frac{d^2\varphi(\omega)}{d\omega^2} \propto I(\omega), \tag{1}$$

then the pulse shape becomes a square for any arbitrary spectrum $I(\omega)$.

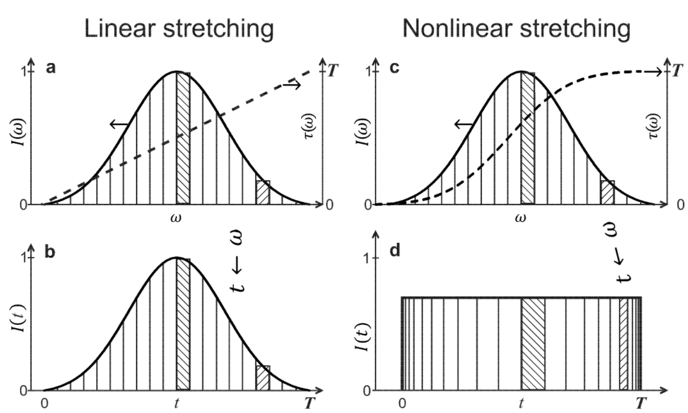

Fig. 2. Pulse stretching with linear chirp. a, b; or with a nonlinear function c, d based on Eq. (1). The dashed line corresponds to $\tau(\omega)$.

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The duration of the stretched pulse is the difference between delay values for the limits $T = \tau(\omega_{max})$- $\tau(\omega_{min})$, see Fig. 3(b). To satisfy this condition for the pulse duration T, the delay and the spectral phase should have the following forms, respectively:

$$\tau(\omega) = \frac{d\varphi(\omega)}{d\omega} = T\frac{\int_0^\omega I(\omega')d\omega'}{\int_0^\infty I(\omega)d\omega}, \tag{2}$$

$$\varphi(\omega) = \int_0^\omega \tau(\omega')d\omega'. \tag{3}$$

In Fig. 3 we show numerical simulations of how the initial pulse spectrum is set equal to the second derivative of the phase (Fig. 3(a)) and is used to determine the spectral delays (Fig. 3(b)), which then are used to generate the spectral phase (Fig. 3(c)). Note that we can reverse direction of the frequency stretching by using phase distortion with opposite sign; this compresses the pulse to its original duration and shape as will be shown below.

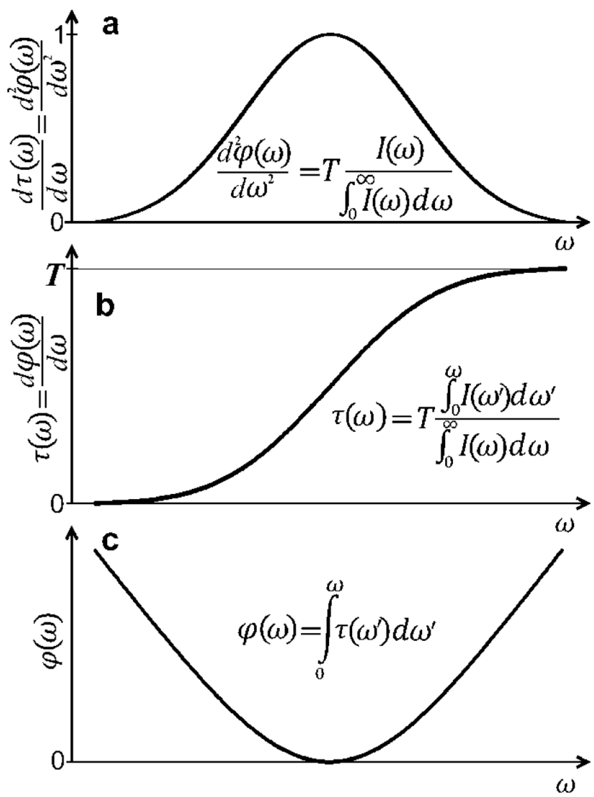

Fig. 3. Phase modulation in the frequency domain to generate square pulses in the time domain. a. Second derivative of the phase, equivalent to the local stretching; b. First derivative of the phase, equivalent to delay of the frequency components; c. Spectral phase required to convert the original pulse into a square pulse in the time domain.

The proposed method works well for large stretching ratios T/τ >10, where τ is the initial pulse duration (FWHM). For smaller stretching ratios the pulse profile is limited by the inherent rise time of the pulse. We simulate the pulse profiles for different stretching factors in Fig. 4, where we changed the initial pulse durationτ while keeping the final pulse duration T the same. Note that for T/τ >10 the approach works very well.

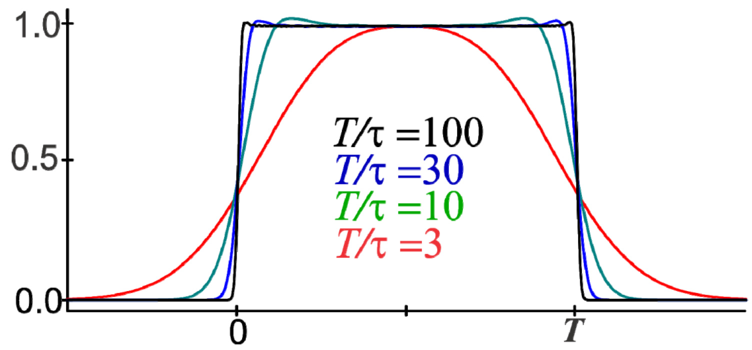

Fig. 4. Pulse in time domain with different stretching parameters.

3. Experimental results

Implementation of the expressions given above in the laboratory is straight forward when using a well calibrated pulse shaper that is capable of eliminating unwanted phase distortions (starting with a Fourier-limited pulse). In our group we rely on multiphoton intrapulse interference phase scan (MIIPS) [12–14]. The experimental setup shown in Fig. 5 consists of a Ti:Sapphire oscillator (Micra, Coherent, Inc.), a pulse shaper (FemtoFit, BioPhotonic Solutions, Inc.), and a Ti:Sapphire regenerative amplifier (Legend, Coherent, Inc.). The output is split into two beams that form a cross-correlator, shown in a Fig. 5 as '1' and '2'. Beam 1 goes through an optical delay line; beam 2 goes through a second pulse shaper 2 (MIIPS Box640 PA, BioPhotonic Solutions, Inc.) where the desired phase is introduced. Both beams are then focused in nonlinear crystal (KDP crystal) by a 400mm focal length lens. The second-harmonic signal is recorded with a spectrometer (USB 4000, Ocean Optics). Pulses in both beams are first compressed to transform limited duration (40fs at FWHM) by running MIIPS in Pulse Shaper 1 and 2, respectively) [12–14].

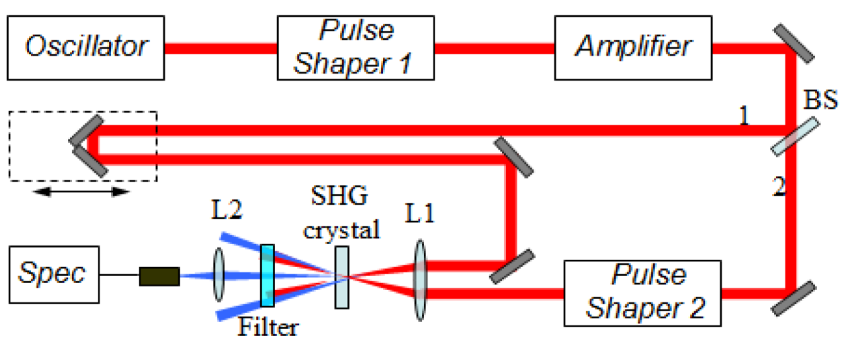

Fig. 5. Experimental setup. BS, beam splitter; L1, L2 are lenses; Beams 1 and 2 after beam splitter are recombined at the SHG crystal, where the pulses are measured.

Experimental demonstration of square pulse generation is shown in Fig. 6(a), where the black curve shows the cross-correlation measurement of the resulting square pulse. The blue curve shows the cross-correlation of the input transform-limited pulses, and the red curve shows linearly chirped pulse with $-39{,}000\text{fs}^2$. Both square and linearly chirped pulses have the same peak power and energy. The phase mask for the square pulses is calculated according to Eq. (1) using the experimental laser spectrum and selecting the desired duration. The phase is introduced by Pulse Shaper 2. Figures 6(b) and 6(c) show the spectrally resolved cross-correlation for both the square and linearly chirped pulses, respectively. From these plots one can see that the SHG intensity is evenly distributed in time within the 3ps window for the square pulse, however, for the chirped pulse the SHG is concentrated within the central picosecond. This illustrates how the square pulse distributes more evenly the peak intensity. Note that phase modulation does not affect the SHG laser pulse spectrum, or the fundamental (800nm wavelength range) spectrum.

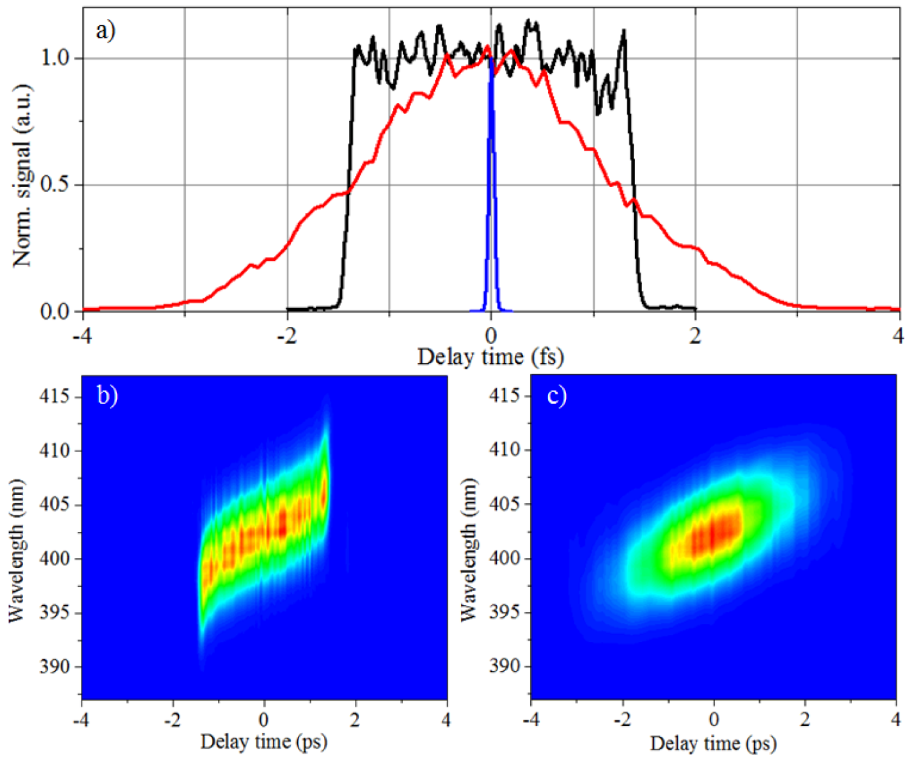

Fig. 6. Experimental cross-correlation measurements. (a) Integrated SHG intensity for the input transform limited pulse (blue), the linearly chirped pulse (red) and the square pulse (black) as a function of delay. (b) Spectrally resolved cross-correlation measurements of the square pulse; (c) Spectrally resolved cross-correlation measurement of the linearly chirped pulse.

The approach described for generating square pulses is only limited by the number of pixels in the pulse shaper. A non-pixelated device such as a deformable mirror does not have this limitation. The maximum stretching factor T_{max}/τ equals the number of pixels within the FWHM of the laser spectrum. We show experimental results for stretching a 40 fs pulse 75, 100 and 150 times in Fig. 7. The results are plotted in logarithmic scale to show the very sharp turn on-off of the pulses and the low background without satellite pulses. No additional special effort was made to reduce the background level below 1% beyond the square pulses. In Fig. 7 (right) we also show that the proposed method for creating stretched square pulses does not affect the fundamental laser spectrum, therefore, the pulses can be recompressed.

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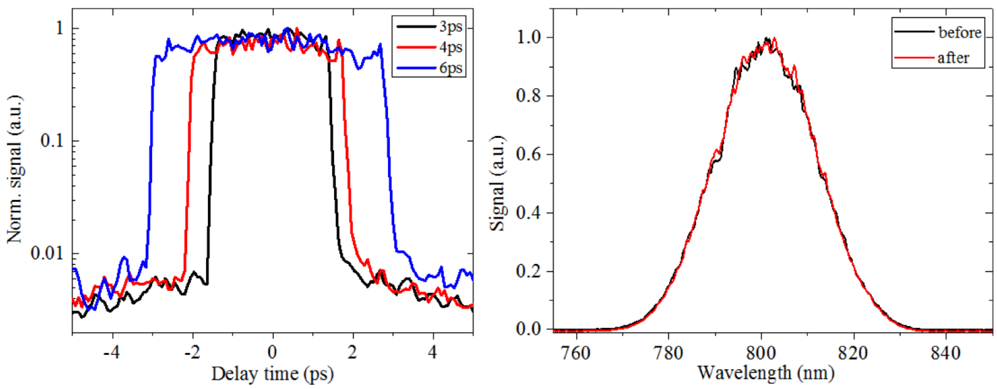

Fig. 7. (Left) Experimental cross-correlation measurements (logarithmic scale) of square pulses with 3ps (black), 4ps (red) and 6ps (blue) pulse duration in. The input pulses had a pulse duration of 40 fs. (Right) Fundamental laser spectrum before and after 10x stretching showing the phase required to create square pulses described here does not affect the pulse spectrum.

One of the motivations for phase-only square pulse generation is that the pulses can be fully recompressed. We test this hypothesis by introducing the phase desired to create 10X stretched pulses at the output of the amplifier using Pulse Shaper 1. We then use Pulse Shaper 2 to recompress the pulses. In Fig. 8(a) we show the phase applied by Pulse Shaper 1, and the phase retrieved by Pulse Shaper 2 in order to recompress the pulses. Note that it is essentially the same phase as introduced by Pulse Shaper 1. Figure 8(b) shows the autocorrelation of the pulses without stretching, and after stretching by Pulse Shaper 1 and recompression by Pulse Shaper 2. Figure 8 shows the hypothesis is correct. Full implementation of this approach for CPA will require considerable thought regarding the most reliable and cost-effective optics to be used for stretching and compression. Similarly, design and cost considerations will determine if the final laser system will include only static optics or if adaptive pulse compression using a programmable pulse shaper will be included.

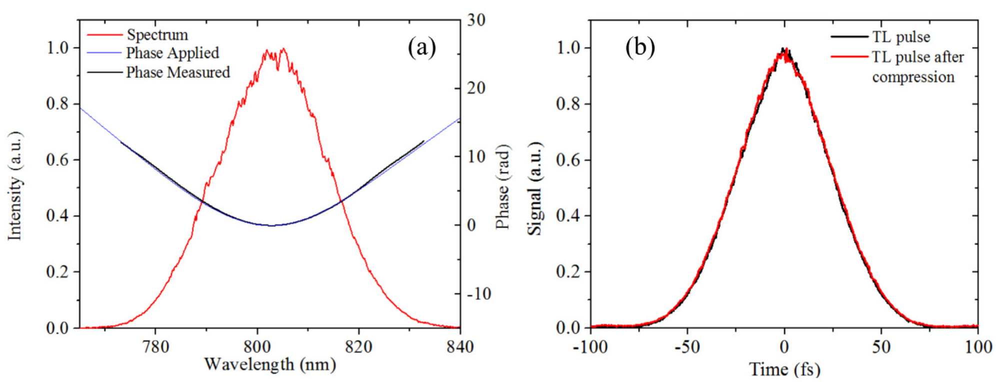

Fig. 8. (a) Experimental spectrum, spectral phase introduced by Pulse Shaper 1 in order to create a 10x square pulse after amplification and spectral phase measured and used by Pulse Shaper 2 to recompress the pulses. (b) Experimental autocorrelation of the amplified laser output pulses without stretching (TL) and after 10x square-pulse stretching by Pulse Shaper 1, amplification, and compression by Pulse Shaper 2 to TL duration.

4. Conclusion

We present an analytic solution to the generation of square pulses in the time domain starting from essentially any arbitrary spectrum. The premise of the work presented here is that self-action depends on the peak intensity of a pulse and that linear chirp may not be the most

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efficient approach to mitigate self-action processes like self-focusing. Numerical results (Figs. 1 and 6) and experimental results testing this hypothesis (Fig. 6) demonstrate that square pulses, results in significantly more compact pulses in the time domain than corresponding linearly chirped pulses. Of particular importance is that the approach presented causes no spectral bandwidth loss and can be reversed to obtain the original input pulse by introducing the complementary phase to the one used to stretch the pulse (Figs. 7 and 8).

Applications of our findings range from an alternative to CPA amplification to other applications where self-action mitigation is important, for example, fiber optic communications and nonlinear optical imaging using a fiber-based endoscope. When comparing a chirped pulse to a square pulse with the same peak intensity, the square pulse has a three times smaller temporal dimension, and because it requires less stretching a smaller spectral dimension on the compression grating. Flat top picosecond laser pulses with fast rise and fall times are desirable for the production of high-brightness electron beams for free-electron lasers, Compton scattering light sources, and MeV electron microscopes [15–17]. There are other scientific applications for pulses with very fast turn on/off, for example, quasi-phase-matched conversion to soft x-ray photon energies, where the fast turn on initiates ionization and the flattop maintains high-peak intensity [18], and time-resolved coherent anti-Stokes Raman scattering [19]. The square pulses produced here can be made to slant from high to low intensity or vice versa. Doing so could optimize many other processes where a fast/slow-rise and slow/fast decay are needed. From a practical sense, while the use of a dedicated pulse shaper is ideal for the implementation of the approach presented here to create stretched square pulses, having an analytic solution should simplify the implementation of this approach for stretching and compressing ultrafast pulses using specially designed dispersive optics such as chirped mirrors and volume/fiber Bragg gratings that take into account the spectrum of the input pulse. One could also conceive of combinations of static optics or specially designed mirrors with the desired curvature for stretching and re-compression.

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