Symmetrical waveform generation based on temporal pulse shaping using amplitude-only modulator

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Symmetrical waveform generation based on temporal pulse shaping using only an amplitude modulator is proposed and investigated. The fundamental principle of this technique is that the Fourier transform of a real and symmetrical waveform is still real and symmetrical. Therefore, it is possible to use an electro-optic modulator that is biased at the minimum transmission point to perform temporal spectrum shaping with a real signal that has both positive and negative values. The proposed approach provides a simple and effective solution to ultrashort symmetrical waveform generation.

Introduction: Spatial light modulator (SLM)-based sub-picosecond pulse shaping for arbitrary waveform generation, which has been extensively investigated in the last few years, can find many scientific and industrial applications [1]. In an SLM-based pulse shaping system, waveform synthesis is performed by spatially modulating the spatially dispersed optical spectrum of an input ultrashort pulse. The major advantage of the SLM-based pulse shaping technique is that the pattern on the SLM can be easily updated, leading to the generation of different waveforms in real time. However, a pulse shaping system using an SLM involves space-to-fibre and fibre-to-space coupling, which makes the system bulky and complicated. Pulse shaping can also be realised in the time domain by using a temporal pulse shaping (TPS) system. A typical TPS system consists of two conjugate dispersive elements (i.e. with dispersions of equal magnitude but opposite sign) and an electro-optic modulator (EOM) that is placed between the two dispersive elements. In the system, an ultrashort optical pulse is temporally stretched and spectrally dispersed by passing through the first dispersive element; then the dispersed pulse is spectrum shaped in the time domain by modulating the spectrum with a radio frequency (RF) signal at the EOM; the temporal compression is realised by passing the spectrum-shaped pulse through the second dispersive element. At the output of the system, a waveform that is the Fourier transform of the RF signal applied to the EOM is obtained. The concept of the TPS was originally proposed by Heritage and Weiner in [2]. Recently, a comprehensive investigation of a TPS system with a microwave tone input at the EOM was performed by Saperstein *et al.* in [3], in which the generation of a number of ultrashort pulses is demonstrated. If the EOM in the system is a phase modulator, more ultrashort pulses with controllable repetition rate can be generated owing to the nonlinearity of the phase modulation [4].

The approaches in [3, 4] were proposed for the generation of ultrashort pulses where a microwave tone is applied to perform TPS. On the other hand, it is highly desirable that the TPS system can be used to generate other types of waveforms such as square waves, rectangular waves or doublets. We demonstrate in this Letter, for the first time to the best of our knowledge, that an arbitrary *symmetrical* waveform can be generated using a TPS system with an amplitude-only modulator (without the requirement of a phase modulator). As is known, in the case of the SLM-based approach, to achieve the same function, both amplitude modulator and phase modulator are usually required [1]. This interesting difference comes from: (i) the Fourier transform of any real and symmetrical signal is still real and symmetrical; and (ii) a temporal amplitude modulator, such as a Mach-Zehnder modulator, when biased at the minimum transmission point, can perform modulation with a modulating signal having either positive or negative values. In contrast, in an SLM-based system, the SLM transmission is always positive, which necessitates the use of an additional phase modulator to achieve negative transmission (phase inversion).

Theory: The schematic diagram of the TPS system for symmetrical waveform generation is shown in Fig. 1. The system consists of a modelocked laser, two conjugate dispersive elements, an amplitude EOM, and a pattern generator. Note that the modulator is biased at the minimum transmission to achieve real signal modulation (with positive and negative values), as shown in the inset of Fig.1. Assume that the input optical pulse is a transform-limited Gaussian pulse that is expressed as $g(t)=\exp(-t^2/\tau_0^2)$, where τ_0 is the half width at $1/e$ maximum. Its Fourier transform is given by $\tilde{G}(\omega)=\sqrt{(\pi)}\tau_0\exp(-\tau_0^2\,\omega^2/4)$. The transfer functions of the first and the second dispersive elements are, respectively, given by

$$H_{\ddot{\Phi}}(\omega)=\exp(-j\ddot{\Phi}\omega^2/2) \quad (1)$$

and

$$H_{-\ddot{\Phi}}(\omega)=\exp(j\ddot{\Phi}\omega^2/2) \quad (2)$$

where $\ddot{\Phi}$ and $-\ddot{\Phi}$ are, respectively, the total dispersions of the two dispersive elements. If an RF signal $x(t)$ is applied to the EOM, the Fourier transform of the signal $q(t)$ at the output of the EOM can be expressed as

$$\tilde{Q}(\omega)=(1/2\pi)\left[\tilde{G}(\omega)H_{\Phi}(\omega)\right]*\tilde{X}(\omega) \quad (3)$$

where $\tilde{X}(\omega)$ is the Fourier transform of $x(t)$ and $*$ denotes the convolution operation. If $|\tau_0^2/\Phi|<<1$ is satisfied and the spectrum of $x(t)$ is confined to a small spectral range such that $\tau_0\,\omega_m<<1$, where ω_m is the maximum frequency of $x(t)$. By employing a similar treatment as in [5], the convolution integral in (3) can be approximated as (Fraunhofer approximation)

$$\tilde{Q}(\omega)\simeq\tilde{G}(\omega)\exp(-j\ddot{\Phi}\omega^2/2)x(\ddot{\Phi}\omega) \quad (4)$$

Therefore, the spectrum of the output signal can be expressed as

$$\tilde{Y}(\omega)=\tilde{Q}(\omega)\times H_{-\ddot{\Phi}}(\omega)=\tilde{G}(\omega)\times x(\ddot{\Phi}\omega) \quad (5)$$

And the corresponding temporal signal is given by

$$y(t)=(1/|\ddot{\Phi}|)g(t)*\tilde{X}(t/\ddot{\Phi}) \quad (6)$$

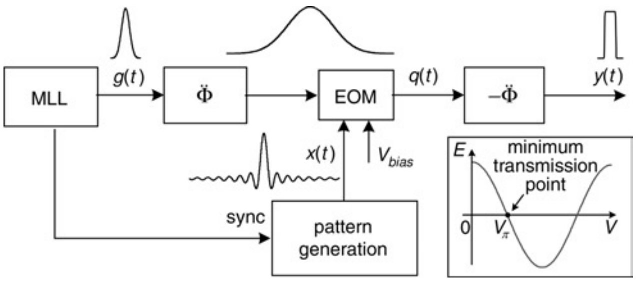

Fig. 1 *Schematic diagram of temporal pulse shaping system for symmetrical waveform generation*

MLL: modelocked laser
EOM: electro-optic modulator
Inset: modulation curve of amplitude EOM

In general, the RF signal $x(t)$ should be a complex signal for arbitrary waveform generation, which could be implemented using an amplitude modulator and a phase modulator. The use of an amplitude modulator and a phase modulator makes the system very complicated, especially as a precise synchronisation between the amplitude and the phase signals must be ensured. For many applications, however, the waveforms are inherently symmetrical, such as square waves, rectangular waves or doublets. It is known that, for a real and symmetrical signal, its Fourier transform is also real and symmetrical. It is therefore possible to generate a symmetrical waveform with a real and symmetrical modulating signal using only an amplitude modulator.

Results and discussion: In the simulation, we assume that the input optical pulse has a Gaussian envelope with an FWHM of 350 fs and the EOM is biased at the minimum transmission point, and linear modulation is considered. The chromatic dispersion $\ddot{\Phi}$ is set to be 1000 ps^2. We then test this technique with different input RF waveforms. The first example demonstrates the generation of a square wave. A *sinc* function is applied to the EOM, as shown in Fig. 2*a*. The expected square wave is obtained, as shown in Fig. 2*b*. In the second example, a triangle waveform is generated, as shown in Fig. 3. It is shown that the generated pulse widths are much narrower than those of the input modulating signals; therefore a high-frequency waveform can be generated using a low-frequency signal in a TPS system.

The waveforms calculated based on (5) match well with the presented simulation results.

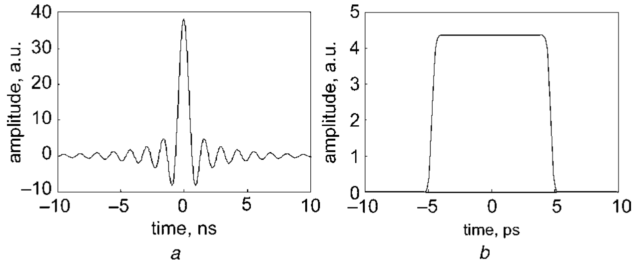

Fig. 2 *Generation of square wave*

a Input *sinc* function applied to EOM
b Generated square wave

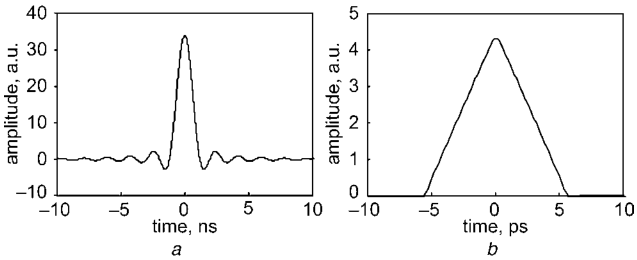

Fig. 3 *Generation of triangle waveform*

a Input RF signal applied to EOM
b Generated triangle waveform

Note that, for both cases, the input signals $x(t)$ are real, therefore the spectrum shaping can be implemented using only an amplitude modulator. In the SLM-based approaches, however, to generate waveforms such as a square wave or a triangle wave, both an amplitude modulator and a phase modulator are usually required [1]. Although phase-only modulation can also generate a large variety of waveforms in the SLM-based systems, there is no a direct analytical solution to derive a phase shift function that can approximate the desired output waveform. Instead, a time-consuming optimisation algorithm, such as a genetic algorithm, should be used [6].

Conclusions: We have proposed an approach to generating symmetrical waveforms based on temporal pulse shaping using only an amplitude modulator. The concept was verified by numerical simulations. This approach, although limited to symmetrical pulse shaping, provides a simple and effective solution to generate ultrafast pulses with many potential applications.

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