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A shaper for providing long laser target waveforms

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Abstract

We discuss the features of a shaping device consisting of a spectral amplitude modulator followed by a pair of diffraction gratings arranged as a linear dispersive stretcher. The proposed system is aimed at transforming input short pulses into long target pulses. The basic of the shaper is the construction of an amplitude profile in the frequency domain and the reproduction of the profile in the time domain. The foreseen characteristics of mechanical simplicity, stability to parameters perturbations and the capability of providing long rectangular pulses with fast rise-time make the device interesting for laser systems devoted to irradiation of radiofrequency electron gun photocathodes.
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1. Introduction

Shaping systems are developed since a decade for narrowing laser pulses used in ultra-fast spectroscopy and non-linear optics [1,2]. Laser waveforms required in high brilliance radiofrequency electron guns (RF-guns) are, on the contrary, relatively long (some picoseconds and longer) and rectangular with a rise time less than 1 ps [3–7]. In fact, a laser pulse driving an RF-gun must have a length covering typically $\frac{1}{30}$ of the RF-period. Being the most widely developed an S-band (≈ 3 GHz) RF-gun, the laser pulse must be as long as 10 ps. An 11 GHz system is in progress at SLAC but the other used systems are superconducting and thus operate at much lower frequency. The requirement of an almost perfect rectangular shaped light pulse, therefore of a photo-generated electron beam of the same shape (rise and falling time less than 1 ps), is due to the fact that a rectangular profile minimizes the defocusing space-charge force, with the consequent reduction of emittance growth [8]. Long rectangular pulses indicate that the shaping system must both greatly enlarge the laser pulses and

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transform them from Gaussian-like to rectangular form. The shaping system we present here is tailored for long pulses generation. Its operation is based on an amplitude spectral modulation, made by the so-called 4f-system [1], followed by a linear space dispersion made by 2-grating stretcher (2g-stretcher) [2].

We observe that UV radiation is required for irradiating RF-gun cathodes. The lasers used for these applications are either Ti:Sa or Nd:YLF (or other of this class). Hence, the light pulse is up-converted to the third harmonic in the Ti:Sa laser case, or to the fourth harmonic in the other case. In the frequency up-conversion the input pulse form is changed by the non-linear interaction within the harmonic generating crystal. In a short-length interaction, equal less than 200 μm, the rectangular form is maintained, the rise time is even shortened, see below. In an interaction length long enough for a relatively high efficiency in harmonic generation, i.e. longer than 500 μm, the flat top moves to a round top and the rise time increases. A way to get round of the two deformations could be the operation in saturation regime, but in this regime the so-called beam break-up is likely to occur.

2. The approach and the relative shaper scheme

Our shaping problem is conveniently separated into (a) the transformation of a short pulse into a long pulse and (b) the transformation of a Gaussian form into a target form. The first task can be obtained by a 2g-stretcher which does a linear dispersion of the pulse spectral components. In fact, it provides a linear delay time among the spectral components

$$\tau(\omega) = \alpha\omega, \tag{1}$$

referred to the central frequency ω_0, thus obtaining the spectral phase function

$$\phi(\omega) = \int_0^{\omega} \tau(\omega')\,\mathrm{d}\omega' = \frac{1}{2}\alpha\omega^2. \tag{2}$$

The latter task implies a proper spectral amplitude modulation. In mathematical terms an operator $H(\omega)$ has to act on the input amplitude spectral function $A_\mathrm{i}(\omega)$ in such a way to get the wanted output spectral function $A_\mathrm{o}(\omega)$

$$A_\mathrm{o}(\omega) = H(\omega)A_\mathrm{i}(\omega). \tag{3}$$

Therefore, we must add a proper amplitude modulator to the 2g-stretcher. The shaping apparatus we are proposing consists of a 4f-system followed by a pair of diffraction gratings as shown in Fig. 1. The 4f-system, arranged in the configuration known as "zero dispersion pulse compressor", has the shaping mask at the focal plane [1] (center plane of the system) programmed as an amplitude modulator. The grating pair is set in a dispersive configuration so to behave as a stretcher with a linear time delay of the pulse spectral components. We call this shaper, composed with the two items, 4f–2g-system. The amplitude and phase modulations are decoupled from one another, as are Eqs. (1) and (3). The amplitude modulating function $H(\omega)$ in Eq. (3) is called filtering function.

2.1. The operation of a 4f-system as amplitude modulator

The operation of a 4f-system is described in detail in Ref. [4]. Briefly, the spectral components of a pulse are first individually focused at the mask pixels, see Fig. 2, and then filtered according to the mask filtering function $H(\omega)$. The spectral focalization (by a lens) in connection with the insertion within the system of a proper mode filter select out of the mask the lowest TEM_{00} mode [1,9]. Hence,

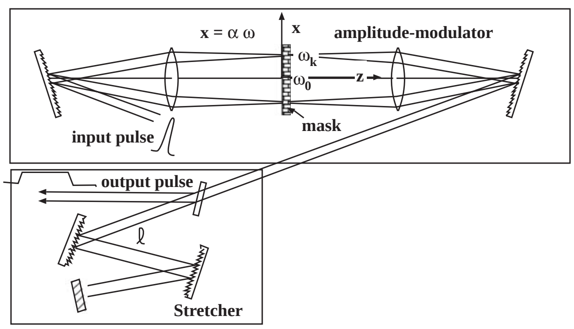

Fig. 1. Sketch of the new shaping system for long pulses. The amplitude modulator sub-part is a 4f-system, the second sub-part is the usual 2-grating apparatus for a linear time delay of the spectral components.

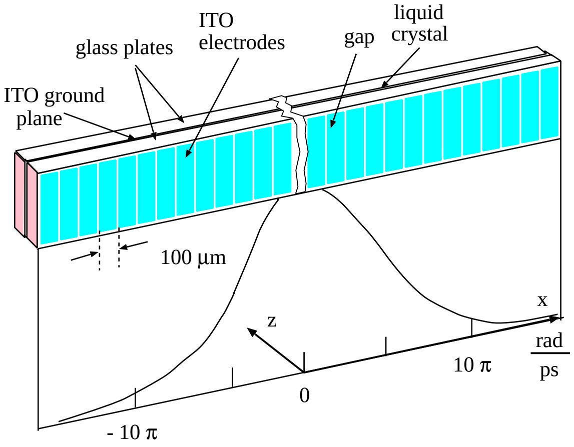

Fig. 2. Sketch of a 4f-system mask.

the filter function has the following expression:

$$H(\omega) = \sqrt{\frac{2}{\pi w_0^2}} \int_{\text{mask}} M(x)\, \mathrm{e}^{-2(x-\beta\omega)^2/w_0^2}\, \mathrm{d}x. \tag{4}$$

Here w_0 is the beam waist of the focused beam at the masking plane (typically 20–100 μm), $M(x)$ is the physical masking function and β is the spatial dispersion of the pulse spectral components introduced by the grating coupled with the lens, that is $x(\omega) = \beta\omega$.

When w_0 is less than the pixel dimension Δx, the following approximation holds [1]:

$$H(\omega) \sim M[x(\omega)], \tag{5}$$

that is, the filtering function $H(\omega)$ is equal to the physical function $M(x)$ of the mask. We choose this operating condition for our system.

The output intensity $I_\mathrm{o}(t)$ is found by performing the inverse Fourier transform

$$I_\mathrm{o}(t) = \left| \int H(\omega) A_\mathrm{i}(\omega)\, \mathrm{e}^{\mathrm{i}\alpha/2\omega^2} \mathrm{e}^{-\mathrm{i}\omega t}\, \mathrm{d}\omega \right|^2. \tag{6}$$

When the output pulse length is much longer than the input pulse length, which means a large α, the integral in Eq. (6) can be written as

$$I_\mathrm{o}(t) \approx \{H[\omega(t)] A_\mathrm{i}[\omega(t)]\}^2 = \tilde{I}_\mathrm{o}[\omega(t)], \tag{7}$$

where $\omega(t) = t/\alpha$. We observe that the two functions $H(\omega)$ and $A_\mathrm{i}(\omega)$ are real. From this Eq. (7) we get that the temporal profile of the pulse $I_\mathrm{o}(t)$ is equal to the power spectrum $\tilde{I}_\mathrm{o}(\omega)$ profile. We can see that the stretcher simply transfers the spectral amplitude profile into the temporal amplitude profile. This occurs because a 2g-stretcher establishes a linear relation between frequency and time.

The result of Eq. (7) can be understood observing that the term $\exp[\mathrm{i}(\alpha/2)\omega^2 - \mathrm{i}\omega t]$ of Eq. (6) is fast oscillating when ω is far from the value t/α, it is, instead, relatively smooth around t/α, see Fig. 3. Thus, that term operates, in a certain sense, as a $\delta(\omega - t/\alpha)$ function. This holds when $A_\mathrm{o}(\omega)$ is smooth enough compared with that exponential term. In fact, the integral where the function is fast oscillating is near zero. This implies a short input pulse (i.e. wide $A_\mathrm{o}(\omega)$) and a long output pulse (i.e. large α).

3. Some useful cases and sensitivity considerations

We discuss some practical cases with the aim of gaining a deeper insight into the physics of the 4f–2g-shaping-system. From Eq. (7) the filtering function turns out to be

$$H(\omega) = \frac{\sqrt{\tilde{I}_\mathrm{o}(\omega)}}{A_\mathrm{i}(\omega)} = \frac{A_\mathrm{o}(\omega)}{A_\mathrm{i}(\omega)}. \tag{8}$$

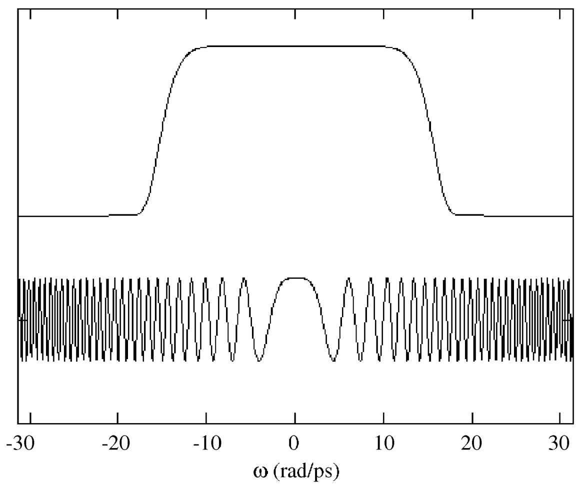

Fig. 3. The upper curve is the output spectral amplitude $A_\mathrm{o}(\omega)$, the lower curve is the $\mathrm{RE}\{\exp[\mathrm{i}(\alpha/2)\omega^2 - \mathrm{i}\omega t]\}$ function. The fast oscillating behavior of this second curve everywhere but the center explains the non-null contribution to the integral (6) only at the center coordinate t/α.

The equation suggests that the equality of $\tilde{I}_o(\omega)$ (the target spectral intensity profile) with $I_o(t)$ (the target temporal intensity) implies to design this target profile inside the spatial frequency spectrum $A_i(\omega)$ curve. We start considering a rectangular target pulse (important for RF-guns) and a transform limited Gaussian input pulse with spectral amplitude $A_i(\omega)$. The Fourier spectrum in frequency of both the input and output signals is depicted in Fig. 4 left frame. In looking for an Δt wide pulse out from the stretcher, the relative α parameter after Eq. (1) must be

$$\alpha = \frac{\Delta t}{\Delta \omega}. \quad (9)$$

Here $\Delta\omega$ is the $A_o(\omega)$ bandwidth as shown in Fig. 4. Five numerically calculated signals out from the stretcher arranged for having lengths in the interval 2–10 ps (the input signal is the one of Fig. 4) are shown in Fig. 5. We see that the pulse must be longer than 6 ps for having a good flat top. The third harmonic profile is calculated through the cube intensity I^3 of the fundamental. We tested that the six-power field $E(t)^6 = [A\cos[\omega t - \phi(t)]]^6$ did not have important envelope fluctuations during the pulse timewidth. We see from the figure that the rise time is less than 1 ps, as required by a class of RF-guns [5,6].

We apply the procedure to the relevant case of the ramp pulse [10]. As a third example we also report the case of the generation of a sequence of three pulses, with the aim of showing the power of our shaping system. As done in the previous case we have to program a mask filtering function

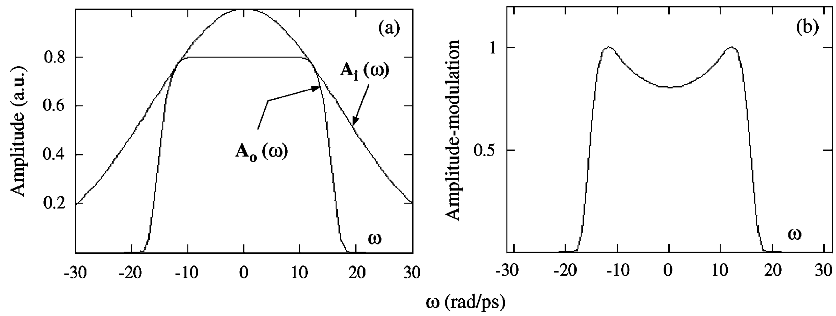

Fig. 4. Left frame shows the input $A_i(\omega)$ (upper curve) and the output $A_o(\omega)$ (inside curve) spectrum amplitudes. $A_i(\omega)$ is a 100 fs wide Gaussian curve and $A_o(\omega)$ has the expression $A_o(\omega) = B\exp(-(\omega/\gamma)^n)$ with $n = 12$ (which means fast rise time). B and γ parameters are chosen to minimize the energy loss. The right frame shows the relative filter function $H(\omega)$.

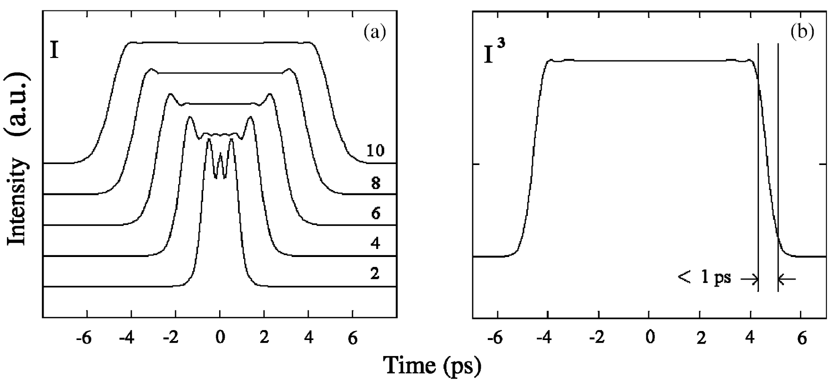

Fig. 5. Left frame depicts the set of output pulses obtained through Eq. (6) with the $A_o(\omega)$ of the previous figure and with different arrangements of the stretcher so to get the pulse durations marked in the curves (Δt = 2–10 ps). Right frame shows the 10 ps long pulse converted to the third harmonic. The rise time (from 10% to 90% of the total pulse height) is less than 1 ps.

$M(\omega)$ leading the target $A_o(\omega)$ to be a ramp (in the first case) and the sequence of pulses (in the second case) inside the input Gaussian spectrum profile $A_i(\omega)$, see Fig. 6. Then, once having chosen the value of the α parameter, we have to solve Eq. (6). The result is depicted in Fig. 7. We chose for this last case an α value such that the output pulse turns out to be as long as 30 ps, with the aim of showing that this shaping system can easily deliver long pulses.

We must remark here that the amplitude modulating mask in laser systems with amplifiers and harmonic generators should be programmable with the aim at compensating the distortions introduced into the pulse by the non-linearities of the amplification and harmonic generation processes. This is the reason of the proposal of the 4f-system with a liquid crystal programmable spatial light modulator (LCP-SLM) in conjunction with a stretcher [1,11]. The LCP-SLM device can be replaced by an optical window with the transmissivity profile found with the above LCP-SLM device, that is a transmission optical element tailored to the specific laser system. The transmissivity will have a super-Gaussian profile with the modifications proper for recovering the distortions introduced in the amplification and frequency conversion processes.

A couple of considerations about the system sensitivity to perturbations are worth doing. One is that the 2f–2g-system is relatively insensitive to parameter perturbations. We observe, incidentally, that it is easy to calculate the effect of the input pulse variations. In fact, once $H(\omega)$, is known for a given modified input $A_m(\omega)$ the output intensity pulse is simply $I_m(\omega(t)) = (H(\omega(t))A_m(\omega(t)))^2$. The change of the output signal profile because of a 0.15 nm shift of the central frequency of the laser

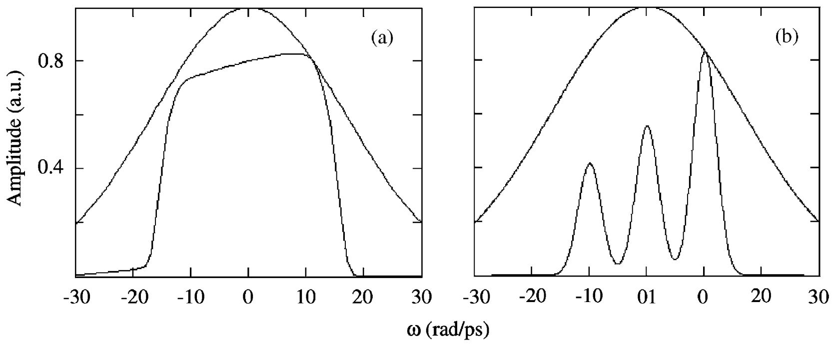

Fig. 6. The figure shows both the input $A_i(\omega)$ and the output $A_o(\omega)$ amplitude spectra (with the Gaussian input pulse) for generating a ramp pulse, frame (a), and a train of three pulses, frame (b), as shown in the next Fig. 7.

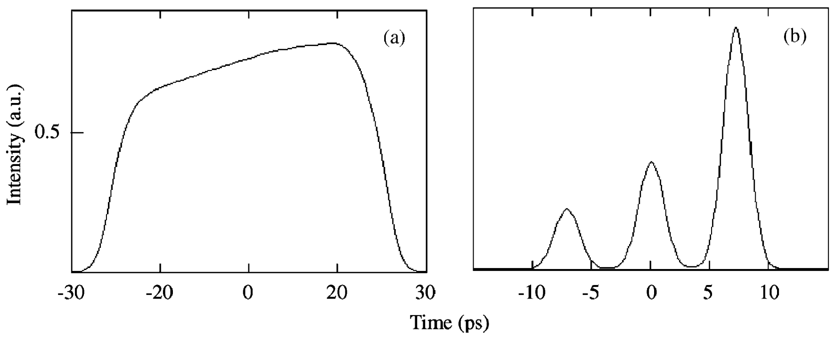

Fig. 7. The figure shows the two output pulses obtained with the amplitude modulation of Fig. 6.

pulse (a value roughly estimated as possible in Ti:Sa laser [12]) is smooth, as shown in Fig. 8. The correspondent variation $(I_{\max} - I_{\min})/I_{\text{average}}$ at the third harmonic is about 20%. This variation is four times less than that obtained with a 4f-system with phase-only-modulation [3]. The sensitivity of the system is reduced by minimizing the spectral interval $\Delta\omega$ selected for the output pulse. We notice that the filtering function will be reprogrammed in the laser operation on the basis of the deformations observed experimentally on the output pulse.

A second consideration is addressed to the perturbation of the input angle θ_i into the stretcher. From the expression of the dispersive coefficient

$$\alpha = \frac{\lambda_0^3 \ell}{\pi c^2 d^2}\left[1 - \left(\frac{\lambda_0}{d} - \sin\theta_i\right)^2\right]^{3/2}, \qquad (10)$$

graphically shown in Fig. 9, we can figure out that choosing a configuration with an input angle greater than 50°the stretcheris practically insensitive to input angle θ_i perturbations. In the above equation λ_0 is the central wavelength, ℓ is the distance of the two gratings (as shown in Fig. 1), c is the speed of light and d is the grating period. We notice that a large input angle in the stretcher means small non-linear terms in the dispersion, thus the delay time $\tau(\omega)$ is linear with frequency to a very good approximation.

4. Conclusions

We have discussed a new conceptual design of a shaping system tailored for relatively long target pulses. The system is important for shaping the rectangular pulses to be applied to radiofrequency electron guns. We have shown via simulations that the system is very efficient for the goal. In fact, it has a simple arrangement, a very low sensitivity to parameters perturbation and provides easily variable pulses of different forms.

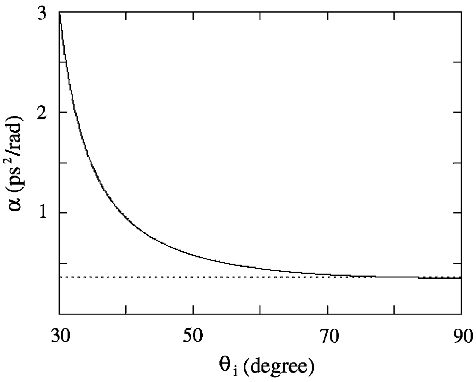

Fig. 9. The figure shows the behavior of the parameter α as function of the input angle having set the distance between the two gratings $\ell = 5$ cm and the period of the gratings 1740 grooves/mm. The dotted line indicates the values which must have the parameter α in order to get a pulse length of 10 ps assuming 10 nm of frequency interval.

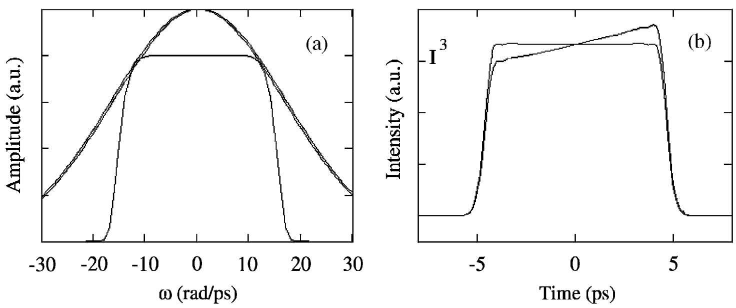

Fig. 8. In left frame (a) the two spectral pulses shifted one another of 0.15 nm are depicted. Inside the input spectrum $A_i(\omega)$ the output spectral amplitude $A_o(\omega)$ is shown. The change of the output intensity waveform (at the third harmonic) due to the central frequency shift is shown in the frame (b). The amplitude percentage variation results about 20%.

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