ISTITUTO NAZIONALE DI FISICA NUCLEARE

Sezione di Milano

INFN/BE-04/01
6 Febbraio 2004

A SHAPER FOR PROVIDING LONG LASER WAVEFORMS

Simone Cialdi, Ilario Boscolo [1]

[1)] *University and INFN, via Celoria 16, 20133 Milano, Italy*

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 system is proposed in view of transforming input short pulses into much longer target pulses. The shaper transfers a spectral amplitude profile into a temporal profile. The device is interesting for its mechanical simplicity, its stability to perturbations of input pulse parameters and optical apparatus alignment and finally for its capability to provide long rectangular pulses with fast rise time as required by radiofrequency electron guns.

PACS.: 42.65.Re, 07.05.Tp

Published by ***SIS–Pubblicazioni***
Laboratori Nazionali di Frascati

1 Introduction

Shaping systems for laser pulse manipulation have a decade of successful development and applications [1]. They are the turn-key for narrowing the laser pulses for ultrafast waveforms (less than 100 fs) used in ultrafast spectroscopy and non-linear optics. 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 [2–6]. This means that the shaping system (in this second application) must greatly enlarge, beyond form, laser pulses. We present here a shaping system tailored for the generation of long pulses. This shaper is in a certain way a synthesis of a 4f-system [1] and a 2-grating stretcher (2g-stretcher) [7].

We observe that UV radiation is required for shining rf-gun cathodes. The lasers used for this 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 forth harmonic in the other case. In the up-conversion the rise time shortens considerably.

2 The approach and the relative shaper scheme

The task we have is the transformation of a short pulse into a long pulse, as well as the transformation of a bell form into a target form. The transformation of a short pulse into a long pulse can be obtained by a linear dispersion of the pulse spectral components. This is routinely accomplished by a 2g-stretcher. It introduces a linear delay time among the spectral components

$$\tau(\omega) = \alpha\,\omega \qquad \text{referred to the central frequency } \omega_0 \tag{1}$$

thus obtaining the spectral phase function

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

A 2g-stretcher is very efficient for providing long pulses. The waveform transformation from a bell form to a target form is obtained by a a proper amplitude modulation of the pulse spectrum. In mathematical terms an operator $H(\omega)$ has to act on the input amplitude spectral function $A_i(\omega)$ to obtain the wanted output spectral function $A_o(\omega)$

$$A_0(\omega) = H(\omega)A_i(\omega) \tag{3}$$

Therefore, we must add to the 2g-stretcher a proper amplitude modulator. The shaping apparatus we are proposing consists of a 4f-system followed by of a pair of diffraction gratings, see Fig. 1.

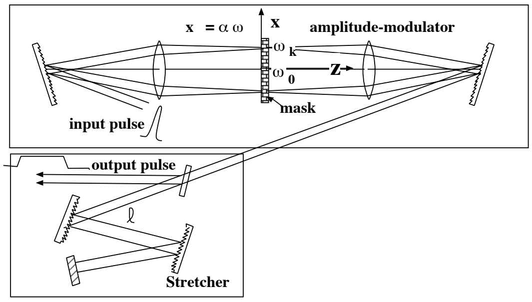

Figure 1: Sketch of the new shaping system for long pulses. The amplitude modulator sub-part is a 4f-system, the second sub-part is the usual 2-grating apparatus for a linear time delay of the spectral components.

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) arranged 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 by an amplitude 4f-component and a 2-grating dispersive stretcher, 4f-2g-system. The idea at the basis of our shaper is that a linear delay time combined with a proper amplitude modulation may provide any target waveform. The two amplitude and phase modulations are decoupled one another. Equation 1 is related to a 2-grating system and Eq. 3 to a 4f-system. The function $H(\omega)$ is the filtering function of the 4f-system which modulate the amplitude of the input pulse.

2.1 The operation of the 4f-system for amplitude modulation

The operations of a 4f-system are described in details in reference [3]. Briefly, in the 4f-system the spectral components of the pulse are individually focused on the mask pixels, see Fig. 2, and then they are filtered according the mask filtering function $H(\omega)$.

The focalization by the lens of the 4f-system and the convenient insertion within the system of a mode filter for selecting only the lowest TEM_{00} mode [1,8], lead to the following filter function

$$H(\omega) = \sqrt{\frac{2}{\pi\, w_0^2}} \int_{mask} M(x)\; e^{-2\,\frac{(x-\beta\omega)^2}{w_0^2}}\; dx \tag{4}$$

where 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

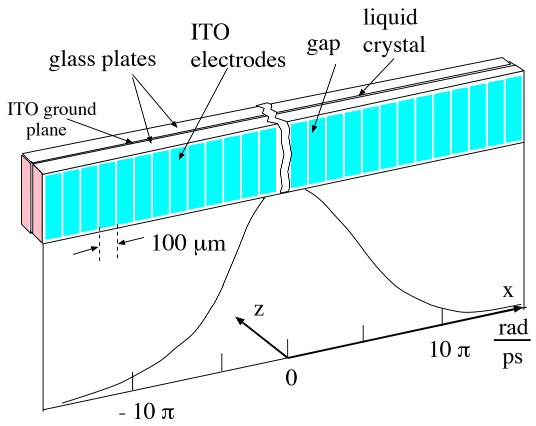

Figure 2: Sketch of a 4f-system mask.

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 condition for our system.
The output intensity $I_0(t)$ is found by the inverse Fourier transform

$$I_0(t) = \left| \int H(\omega) A_i(\omega)\, \mathbf{e}^{\mathbf{i}\,\frac{\alpha}{2}\omega^2}\, e^{-i\,\omega t}\, d\omega \right|^2 \tag{6}$$

When the output pulse length is much longer than the input pulse length, which means a large α, the integral in Eq. (6) ends up to

$$I_0(t) \approx \{H[\omega(t)] A_i[\omega(t)]\}^2 = \tilde{I}_0[\omega(t)] \tag{7}$$

where $\omega(t) = t/\alpha$. We observe that the two functions $H(\omega)$ and $A_i(\omega)$ are real. From this Eq. (7) we get that the temporal profile is that one of the power spectrum $\tilde{I}(\omega)$. 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 $exp[i\,(\alpha/2)\omega^2 - i\omega t]$ 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 $A_0(\omega)$ is smooth enough compared with that exponential term. In fact, the integral

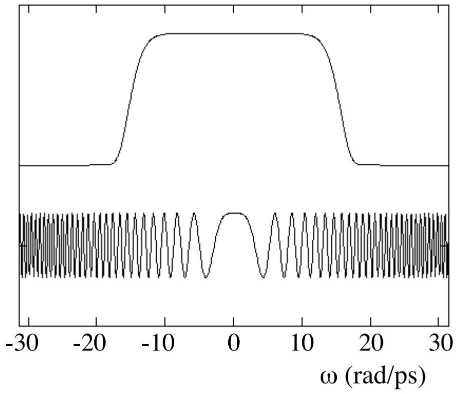

Figure 3: The top curve refers to the function of the output spectral amplitude $A_0(\omega)$, the other curve represents the function $RE\{exp[i\,(\alpha/2)\omega^2 - i\omega t]\}$. It immediate to notice that only the relatively slow oscillating section of this second curve allows the non-null contribution to the integral of the relative part of the upper curve, which is at the value t/α.

where the function is fast oscillating is near zero. This implies a short input pulse (i.e. wide $A_0(\omega)$) and a long output pulse (i.e. α large).

3 Some useful cases and considerations on the sensitivity

We discuss some practical cases with the aim of gaining a deeper insight into the physics of the 4f-2g-shaping-system. Before, we note from Eq. (7) that we get

$$H(\omega) = \frac{\sqrt{\tilde{I}_0(\omega)}}{A_i(\omega)} = \frac{A_0(\omega)}{A_i(\omega)}. \tag{8}$$

We can say that making the profile of the (target) spectral intensity distribution $\tilde{I}_0(\omega)$ equal to the profile of the (target) temporal intensity $I_0(t)$ amounts to design the target profile within the amplitude curve of the spatial frequency spectrum $A_i(\omega)$ of the input signal. 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 the temporal pulse produced by the stretcher, we choose the parameter α of the stretcher congruent with the wanted pulse length. After Eq. (1)

$$\alpha = \frac{\Delta t}{\Delta\omega}. \tag{9}$$

Here $\Delta\omega$ is the bandwidth of $A_0(\omega)$ shown in Fig. 4 , Δt is the time width of the target pulse amplitude. The action of the stretcher for five cases is shown in Fig. 5.

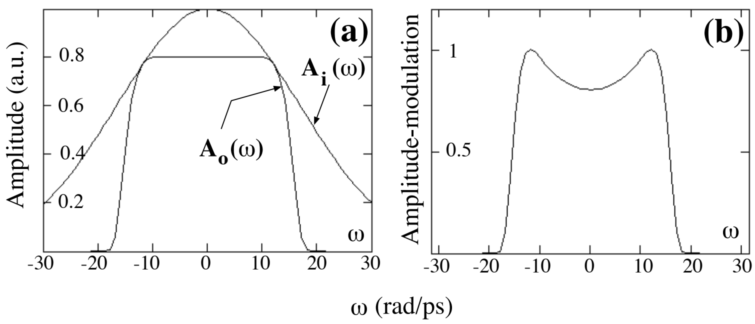

Figure 4: Left frame: the figure shows both the input $A_i(\omega)$ and the output spectrum amplitude $A_0(\omega)$. The Gaussian input pulse is 100 fs long. For the case under consideration we chose $A_0(\omega) = B\,exp(-(\omega/\gamma)^n)$ with n=12 (which means fast rise time). The two parameters B and γ are such that the minimum energy loss occurs. The right frame shows the relative filter function $H(\omega)$.

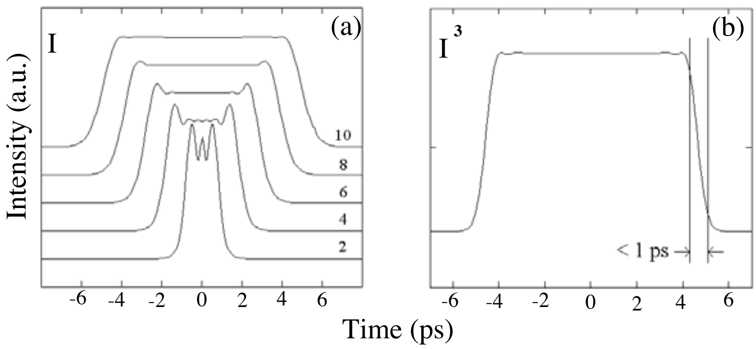

Figure 5: The left frame depicts the set of output pulses, obtained with the general equation (6), referred to the time widths marked in the curves ($\Delta t = 10 - 2\ ps$). The right frame shows the 10 ps long pulse converted to the third harmonic. The rise time (from 10 % to 90 % of the total pulse height) is less than 1 ps.

From the results we see that already at 6 ps pulse length, the shape does not come out completely satisfactory (nicely rectangular). After many simulations we may conclude that our shaping system operates properly in generating rectangular long pulses when the target output pulse length is about a hundred time longer than the input pulse. We remark that the curves depicted in Frame (a) of Fig. 5 are the simulated intensity profiles of the output pulses from the 4f-2g-shaper. The signal of Frame (b) is calculated as the cube intensity I^3. This signal is thought to simulate the output pulse from a third harmonic generator. We see from the figure that the rise time is less than 1 ps, as required by a class of rf-guns [4,5].

We apply the procedure to another case relevant for rf-guns, the ramp pulse [9]. As a third example we report also 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 simply to design a ramp (in the first case) and the sequence of pulses (in the second case) inside the input Gaussian spectrum curve, see Fig. 6.

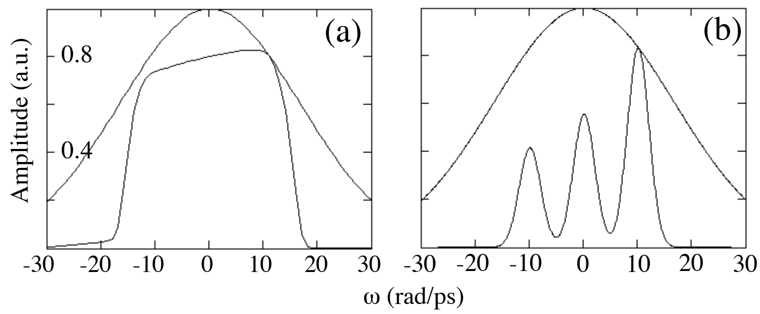

Figure 6: The figure shows both the input $A_i(\omega)$ and the output $A_0(\omega)$ amplitude spectra (with the Gaussian input pulse) for generating a ramp pulse, frame (a), and a train of three pulses, frame (b), as shown in the next Fig. 7.

Then, once 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 in an easy way deliver long pulses (which, by the way, can be useful in superconducting rf-guns).

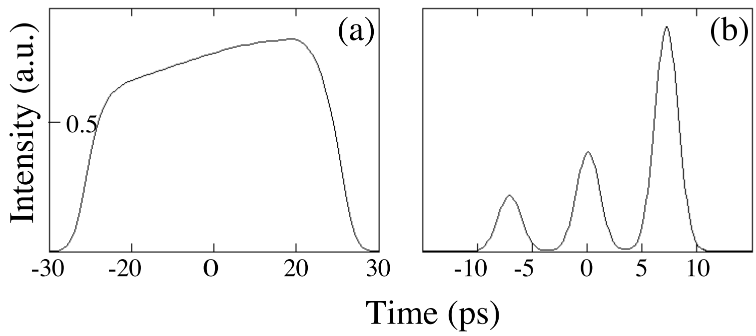

Figure 7: The figure shows the two output pulses, ramp pulse left frame and three pulses right frame, obtained the amplitude modulation of Fig. 6.

We must remark here that the amplitude modulating mask in laser systems with strong amplifiers should be programmable for having the capability to compensate for the pulse distortions introduced by the amplifiers non-linearities. 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 [1,10]. We believe that once found the transmittance spatial pattern required by the operating laser system, an optics specially made with that patterned transmittance could be inserted into the laser system.

A couple of considerations about the system sensitivity to perturbations are worth doing. One is that the 2f-2g-system is relatively low sensible to parameter perturbations.

We observe, incidentally, that it is easy to calculate the effect of the input pulse variations. In fact, once known $H(\omega)$, for a given modified input $A_m(\omega)$ the output intensity pulse is simply $I_m(\omega(t)) = (H(\omega(t))A_m(\omega(t)))^2$. We have considered for a calculation on the sensitivity the variation on the output signal because of a small shift of the central frequency of the laser pulse. Considering a variation of the central frequency of $0.15\,nm$ (a value roughly estimated as possible in Ti:Sa laser [11]) the distortion of the output pulse is smooth, see Fig. 8, and anyway the variation $(I_{max} - I_{min})/I_{average}$ is about 20% at the third harmonic (it is much less at the fundamental). This variation is four times less than that obtained with a 4f-system with phase-only-modulation [2].

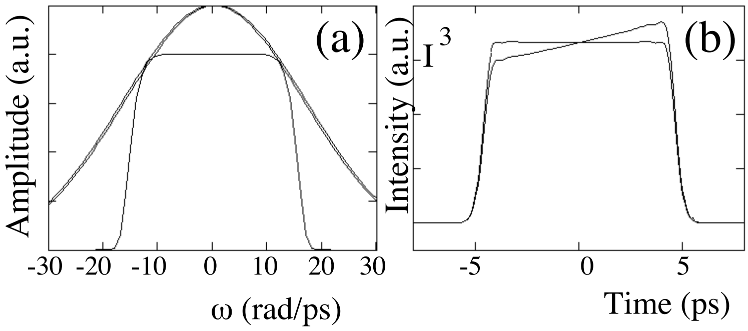

Figure 8: In left frame (a) the two spectral pulses shifted one another of 0.15 nm are depicted. Inside the input spectrum $A_i(\omega)$ the output spectral amplitude $A_o(\omega)$ is shown. The change of the output intensity waveform (at the third harmonic) due to the central frequency shift is shown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

The sensitivity of the system lowers reducing the spectral interval $\Delta\omega$ selected for the output pulse. The calculations refer to a Gaussian input spectrum for simplicity. In an experiment it will be changed by the measured spectrum.

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

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

graphically shown in Fig. 9, we can figure out that choosing a configuration with an input angle greater than fifty degree the stretcher is practically insensible 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 a very good approximation.

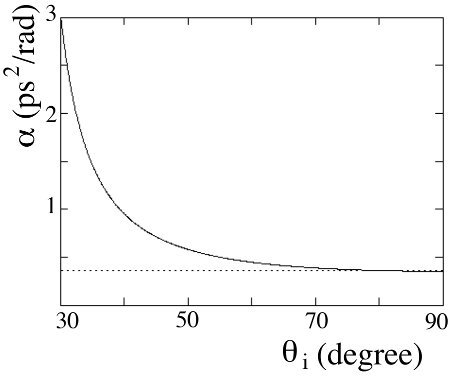

Figure 9: The figure shows the behavior of the parameter α as function of the input angle having set the distance between the two gratings $\ell = 5\,cm$ and the period of the gratings 1740 grooves/mm. The dotted line indicates the α value for obtaining a the length of 10 ps for the pulse with 10 nm frequency interval.

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 is of simple arrangement, has a very low sensitivity to parameters' perturbation and finally it provides easily pulses of different forms.

Acknowledgments

The work is partly supported by MIUR, *Progetti Strategici*, DD 1834, Dec,4,2002.

References

[1] A. M. Weiner, Rev. Sci. Instrum., **71,** 1929–1960 (2000).

[2] S. Cialdi, I. Boscolo and A. Flacco, *Features of a phase-only shaper relative to a long rectangular ultraviolet pulse* report INFN-BE-03-2, sent for pubbl. JOSA.

[3] S. Cialdi, I. Boscolo, *A laser pulse shaper for the low emittance radiofrequency SPARC electron gun*, report INFN-BE-03-3, to appear on NIM Phys. Res. A

[4] SPARC "Conceptual design of a high-brightness linac for soft X-ray SASE FEL source," EPAC 2002 (La Villette, Paris) 5 June 2002.

[5] M. Cornacchia et al., “Linac coherent light source (LCLS) design study report” (Stanford University-University of California) Report No. SLAC-R-521/UC-414, revised 1998.

[6] J. Yang, F. Sakai, T. Yanagida, M. Yorozu, Y. Okada, K. Takasago, A. Endo, A. Yada, and M. Washio, J. Appl. Phys. **92,** 1608–1612 (2002).

[7] S. Backus, C. G. Durfee III, M. M. Murname and H. C. Kapteyn, Rev. Sci. Instrum. **69,** 1207–1223 (1998).

[8] R. N.Thurston, J. P. Heritage, A. M. Weiner and W. J. Tomlinson, IEEE J. Quantum Electron, **22,** 682-696 (1986).

[9] James Rosenzweig, UCLA, private comunication

[10] M. C. Wefers and K. A. Nelson, opt. Lett **18** (1993) 2032.

[11] Comunication by I. Will within LI-ERP Workshop, October 23-25, 2002, SLAC, Stanford, California.