OPTICAL PULSE COMPRESSION BY PHOTONIC DEVICES

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***Abstract*— By combining phase modulation and dispersive transmission on a given time-varying input signal, we propose an optical device for producing ultrashort light pulses of high optical power. We derive the relationship between the required properties of the input signal and the device parameters in order to optimize the energy concentration in the output optical pulses. The high-order aberrations effects of the time lens which perform the phase modulation are considered. Besides, the differences on the obtained pulse shape when the input signal has a gaussian or a super-gaussian envelope are illustrated. Finally, some numerical simulations are shown which illustrate the feasibility of the method.**

***Keynotes* — Optical fiber devices, Optical pulse compression.**

I. INTRODUCTION

The development of techniques for the analysis and synthesis of ultrashort optical pulses has become a subject of the most importance in the field of optical communications, photonic signal processing and ultrafast optics. From the spatial-temporal duality theory (Kolner, 1994; Papoulis, 1994, Bennett and Kolner, 2001; Van Howe and Xu, 2006) well-known concepts and experiments developed in the framework of spatial image processing can be transferred to the temporal domain thereby providing new ways for analyzing and processing temporal optical signals. Among several applications, the temporal Talbot effect (Azaña and Muriel, 2001; Azaña and Chen, 2003; Cuadrado-Laborde *et al.*, 2006; Chantada *et al.*, 2006) and others similar techniques (Torres-Company *et al.*, 2006; Komukai *et al.*, 2005) were implemented in order to produce periodic pulse trains with different repetition rates. The basic components of these temporal devices are dispersion lines, such as optical fibers (OF) or linearly chirped Bragg gratings (LCFG), and time lenses which are basically quadratic phase modulators.

In this paper, we analyze the conditions to be achieved by a photonics device combining phase modulation and dispersive transmission on a certain time-varying input signal for producing ultrashort light pulses with high optical power. Same as periodicity of the input signal assures selfimaging when the Talbot condition is satisfied, energy concentration requires a photonic device acting on the input signal in a similar way as a spatial "diffractive" lens focuses light energy. In Section II we derive the conditions to be fulfilled by the several parameters associated with the setup here proposed, for obtaining well conformed light pulse of high-energy. Besides, we analyze the effect on the pulse shape of the combined action of third- and fourth-order aberrations of the time lens, and the detuning from the proper dispersion value of the dispersive media. In Section III we analyze the system implementation feasibility with real devices (phase modulators and dispersive lines) and the quality of the pulses generated are discussed. In Section IV the pulse generation is analyzed by considering a laser source where the envelope of the emitted signal is a gaussian or a super-gaussian function. Finally, in Section V we present the conclusions of this work.

II BASIC THEORY

Let us consider that the input signal to the system to be analyzed is given by the output of either a continuous (CW) or a pulsed laser centered at the angular frequency ω_0, but modulated with a signal that has a linear frequency variation. Thus, its complex envelope can be written in a general form as

$$X_{in}(t) = A(t)\exp\left(-iCt^2/2T_0^{\,2}\right) \quad , \qquad (1)$$

where we denote as $A(t)$ the baseband amplitude (continuous or pulsed) of the input signal, T_0 is related with the temporal duration of $X_{in}(t)$, and C is a chirp parameter which takes into account a linear frequency variation. This input signal is successively phase modulated by a temporal lens and transmitted through a first-order dispersion line for producing the output signal $X_{out}(t)$. The phase function associated with the optical modulator can be written as $\phi(t) = \phi_{20}\,t^2/2 + \Delta\phi(t)$, where ϕ_{20} is the quadratic modulation factor responsible of the lens action and $\Delta\phi(t)$ is the deviation term (which includes higher orders terms in the Taylor expansion of $\phi(t)$) which can be treated in a similar way as the aberration function is analyzed in spatial imaging. Regarding with the dispersion line, it has associated a quadratic-phase spectral response centered at the mean frequency ω_0 of the input signal, with a second order parameter Φ_{20}. For arbitrary values of the device parameters ϕ_{20} and Φ_{20}, the baseband equivalent amplitude of the output signal becomes

$$X_{out}(t)=\frac{A_D}{\sqrt{2\pi|\Phi_{20}|}}\exp\left(-i\frac{t^2}{2\Phi_{20}}\right)\times$$
$$\times\int_{-\infty}^{\infty}A(\tau)\exp\left[\frac{\tau^2}{2}\left(\frac{C}{T_0^2}+\phi_{20}-\frac{1}{\Phi_{20}}\right)+\Delta\phi(\tau)\right]\times \quad (2)$$
$$\times\exp\left(i\frac{t\tau}{\Phi_{20}}\right)d\tau \quad ,$$

where A_D is the modulus of the transfer function associated with the dispersion line.

In any of the two situations (pulse or CW), the total duration of $X_{in}(t)$, limited by $A(t)$, is restricted by the time aperture *TA* of the time lens, in such a way that the actual duration should be lower that the *TA*. From Eq. (2), in order to obtain an energy concentration in the form of a sharp pulse, the quadratic phase inside the integral should be zero. If we consider that the aberration term $\Delta\phi(t)$ is zero, the following relation should be fulfilled by the dispersion parameter

$$\Phi_{20}=\frac{1}{\phi_{20}-C/T_0^2} \quad . \quad (3)$$

Under the condition of Eq. (3), the output amplitude is basically proportional to the Fourier transform of $A(t)$. By this reason, for simultaneously minimizing the temporal duration of $X_{out}(t)$ and concentrating most of the optical power of $X_{in}(t)$ in the main pulse, $A(t)$ should be ideally given by a continuous or a sinusoidal signal. Thus, the output amplitude becomes

$$X_{out}(t)=\frac{A_D}{\sqrt{2\pi|\Phi_{20}|}}\exp\left(-i\frac{t^2}{2\Phi_{20}}\right)\tilde{A}\left(-\frac{t}{2\pi\Phi_{20}}\right) \quad , \quad (4)$$

where $\tilde{A}(.)$ means the Fourier transform of $A(.)$. Thus, an ultra-short pulse with a high optical intensity can be produced depending on the shape, chirp and duration of the input signal, whenever the system parameters satisfy Eq. (3).

Let us now consider the effect of the higher orders terms in the Taylor expansion of $\phi(t)$, *i.e.*, we analyze the phase modulation function $\phi(t)=\phi_{20}t^2/2+\phi_{30}t^3/6+\phi_{40}t^4/24$, which takes into account the cubic and quartic modulation factors ϕ_{30} and ϕ_{40}. Besides, we analyze the effect of a detuning from the condition of Eq. (3) in the form $\Phi_{20}=1/(\phi_{20}-C/T_0^2)\pm\Delta\Phi$, due to any variation of the quadratic dispersion term. In this case, the term in Eq. (2) that originates the desired energy concentration can be rewritten as

$$X_{out}(t)=\frac{A_D}{\sqrt{2\pi|\Phi_{20}+\Delta\Phi|}}\exp\left(-i\frac{t^2}{2(\Phi_{20}+\Delta\Phi)}\right)\times$$
$$\times\int_{-\infty}^{\infty}A(\tau)\exp\left(i\Delta\varphi\frac{\tau^2}{2}\right)\exp\left(i\phi_{30}\frac{\tau^3}{6}\right)\times \quad (5)$$
$$\times\exp\left(i\phi_{40}\frac{\tau^4}{24}\right)\exp\left(i\frac{t\tau}{\Phi_{20}}\right)d\tau \quad .$$

We initially select *TA* small enough as to neglect the effect of ϕ_{40}. In this case, the output amplitude, as given by Eq. (5), mathematically coincides with the amplitude $u(L;t)$ obtained when a pulse a initial shape $u(0;t)$ is propagated by a certain distance L inside an optical fiber, having dispersion parameters β_2 and β_3 (Agrawal, 2001). Thus, Eq. (5) could be rewritten as: $X_{out}(t)=K\times\exp(-it^2/2\Phi_{20})\times u(L;-t/\Phi_{20})$, being $u(0;t)$ the input "equivalent" transmitted pulse given by $\Im^{-1}\{A(\tau)\}$ ($\Im^{-1}$ denotes the inverse Fourier transform).

The equivalent dispersion parameters are related with the device parameters through: $\beta_2L=2\Delta\varphi$ and $\beta_3L=\phi_{30}$. By taking into account that higher-order dispersion effects become relevant in fiber pulse transmission only if $\bar{T}_0|\beta_2/\beta_3|\le 1$ (being $\bar{T}_0$ a measure of the pulse width) the output signal significantly deviates from the result of Eq. (2) whenever $|\Delta\varphi|\le|\varphi_{30}|/2\hat{T}_0$. In this expression, $\hat{T}_0$ represents the mean time width of $u(0;t)$. Same as it is observed in the dispersive transmission of its "equivalent pulse", $X_{out}(t)$ changes from a symmetrical sharp peak (assuming that $A(t)$ is indeed symmetric) to a non-symmetric shape exhibiting an oscillating structure on one side. For the case of $\phi_{30}>0$, the oscillations occur in the trailing edge of the output pulse. On the other hand, if only the ϕ_{40} contribution is relevant, spherical aberration is observed (same as in spatial imaging) originating two effects (Van Howe, 2006): *i*) The pulse width is increased as compared with the ideal, non-aberrated situation of Eq. (4); and *ii*) The dispersion parameter Φ_{20} required to produce the sharp pulse slightly varies from the value that is obtained from Eq. (3). This last effect is related with the well-known focal-shift that is originated by the fourth-order aberration. These results will be illustrated in the next section.

III. IMPLEMENTATION FEASIBILITY

The achieved results will be illustrated with some numerical simulations. We will compare the results obtained using an ideal modulator with those obtained using an electro-optic modulator (EOM) fed with a sinusoidal phase signal. Besides, we also analyze both, the pulse conformation for a varying dispersion parameter and the effects which are to be present if there exist a detuning in the condition given by Eq. (3).

The input signal envelope was selected as $A\times\mathrm{rect}(t/T_0)\cos[2\pi(f_p+\Delta f_p t)t]$, being A^2 the continuous optical power and the rect(.) function limits the signal temporal duration to $T_0=4$ ns. The linear frequency variation has an initial value $f_p=16.7$ GHz and a change rate $\Delta f_p=2.5\times10^{18}\,\mathrm{Hz}^2$. By selecting $\phi_{20}=10^{18}\,\mathrm{Hz}^2$ the sharp pulse condition is achieved when the dispersion parameter becomes $\Phi_{20}=\Phi_{20}^{(p)}=3.085\times10^4\,\mathrm{ps}^2$. Under this condition, the normalized output intensity when an ideal modulator is used (where the phase modulation function is $\phi(t)=\phi_{20}t^2/2$ and $TA=T_0=4$ ns) is shown in Fig. 1(a). As it is expected from Eq. (3), with $A(t)=A\times\mathrm{rect}(t/T_0)$, the output optical power has a $\mathrm{sinc}^2(.)$ function shape, containing the main lobe around 50% of the input energy and being the FWHM (full wave half medium) width of the pulse $\delta t_{out}\cong 48$ ps. In order to illustrate the required accuracy in the dispersion parameter selection, we also show the output intensity when a ±10% detuning of $\Phi_{20}^{(p)}$ is considered.

Next, for illustrating the aberrations effect in the pulse shape, we consider a real temporal lens given by an EOM having a phase modulation function $\phi(t) = \cos(\omega_m\ t)$, with $f_m = \omega_m/2\pi = 160$ MHz. It should be taken into account that this modulation function has associated the same quadratic coefficient $\phi_{20} = 10^{18}\,\mathrm{Hz}^2$ as in the previous ideal case but, due to the value of ω_m, its free-aberrations TA is restricted to 1 ns ($<T_0$=4ns). As the cosine function is not time-shifted, there is only present ϕ_{40} as lens aberration. Now, the output intensity is shown in Fig. 1(b) and it can be seen that the maximum output is produced for $\Phi_{20} = 1.1\times\Phi_{20}^{(p)}$, as it would be expected due to the spherical aberration “shift effect”. Regarding with the pulse shape, the main lobe of the pulse is practically the same as in the ideal case and the side-lobes are slightly increased. Finally, we consider the more general electro-optic modulation function $\phi(t) = \cos(\omega_m t + \Delta\varphi_0)$, where $\Delta\varphi_0$ is an arbitrary phase shift. As the *cosine* function is now shifted, both coefficients ϕ_{30} and ϕ_{40} are present introducing another lens aberration contribution. In this case, the output intensity is shown in Fig. 1(c) for $\Delta\varphi_0 = \pi/3$, and it can be observed that due to the combined action of both aberrations, the complete pulse is non-symmetrical (see the side-lobes) and it is again formed at $\Phi_{20}= 1.1\times\Phi_{20}^{(p)}$. However, it can be observed that the main lobe remains almost unchanged in any of the three cases. In order to better illustrate the high energy pulse formation, a 3D display of the output intensity is shown in Fig. 2(a) for a continuously varying Φ_{20}, from zero to its maximum value. For $\Phi_{20}=\Phi_{20}^{(p)}=3.085\times10^4\,\mathrm{ps}^2$ a very sharply pulse with a high amplitude is conformed (where Eq. (3) is satisfied), while for $\Phi_{20} > \Phi_{20}^{(p)}$ the pulse intensity rapidly decreases becoming its value negligible as compared with the obtained maximum value. From Fig. 2(a), the maximum output intensity results around twenty times the input intensity, for the selected device parameters.

Finally, we analyze the behaviour of the maximum output intensity when a detuning in Eq. (3) is present due to a variation of the dispersion parameter Φ_{20}. From Fig. 2(b), it can be observed that, by admitting a 50% decreasing of the maximum intensity, it corresponds to a relative variation of the dispersion parameter of ~ 8%, and an absolute variation of $0.25\mathrm{x}10^4\,\mathrm{ps}^2$, which in terms of length of standard optical fiber it is equivalent to 100 km approximately. Therefore, in order to implement the dispersive line, the appropriate photonic device should be a LCFG or a photonic crystal fiber, since the resulting standard optical fiber length is large enough and the nonlinear effects should be considered (Hanna *et al.*, 2005).

IV. SEMICONDUCTOR LASER PULSES COMPRESSION

In the previous sections we found the theoretical conditions for obtaining an ultrashort high pulse when the in

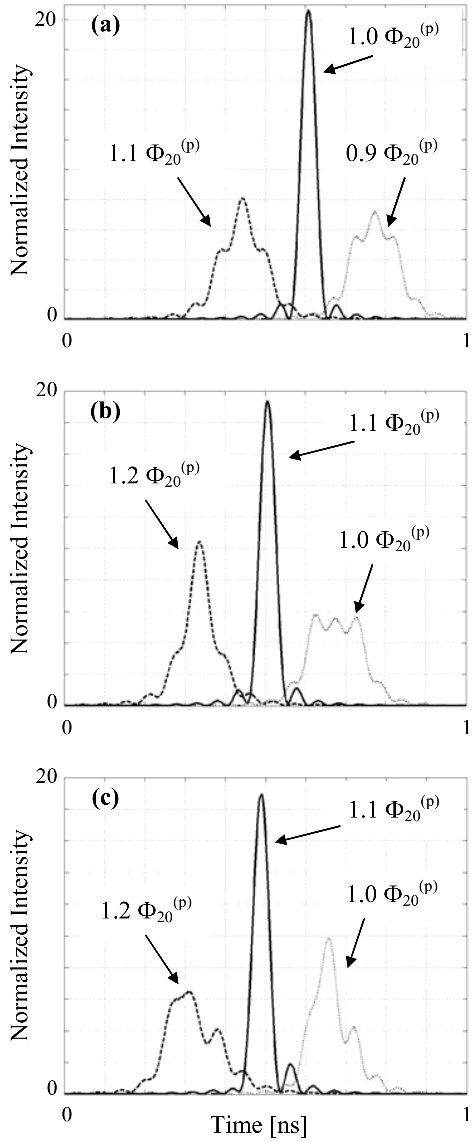

Fig. 1. Output optical power for three different time lens (maintaining constant $\phi_{20} = 10^{18}\,\mathrm{Hz}^2$) having the term Φ_{20} as parameter. (a) For an ideal free-aberrated time lens (TA=4 ns) with $\Phi_{20}=\Phi_{20}^{(p)}=3.085\times10^4\,\mathrm{ps}^2$, $\Phi_{20} = 1.1\times\Phi_{20}^{(p)}$ and $\Phi_{20} = 0.9\times\Phi_{20}^{(p)}$. (b) An EOM with phase modulation $\phi(t) = \cos(2\pi160\ \mathrm{MHz}\,t)$. In this case, due to the spherical aberration shift-effect which is present, the output pulse is formed for $\Phi_{20} = 1.1\times\Phi_{20}^{(p)}$. (c) An EOM with phase modulation $\phi(t) = \cos(2\pi160\ \mathrm{MHz}\,t+\pi/3)$. In this case, the pulse is formed for $\Phi_{20} = 1.1\times\Phi_{20}^{(p)}$ again, but this becomes slightly non-symmetric (see the side-lobes).

put is a bandpass signal with a linear frequency modulation. Now, we analyze the system performance when theinput signal is obtained from a real semiconductor laser which is internally modulated. This optical envelope signal has a considerable frequency chirp and it can be expressed as

$$X_{in}(t) = \Re e\left\{\exp\left(-\frac{1+iC}{2}\left(\frac{t}{T_0}\right)^{2m}\right)\right\} \quad , \qquad (6)$$

where the envelope shape is a gaussian or super-Gaussian function (depending if $m = 1$ or $m = 2; 3; ...$, respectively), and the chirp parameter is estimated from experimental measurements to a value $C \cong$ -6 (Agrawal, 2001). The output signal can be analytically obtained when the coefficient is $m = 1$, but for $m > 1$ the solution can be only obtained by numerical simulation.

Let us consider that the input signal is given as in Eq. (6), with $m = 1$, and it is successively phase modulated and propagated in a dispersive line, in such way that the condition given by Eq. (3) is satisfied. Therefore, the output signal can be written as

$$X_{out}(t) = \frac{A_D T_0}{2\sqrt{|\Phi_{20}|}}\exp\left(-i\frac{t^2}{2\Phi_{20}}\right)\exp\left(-\frac{1}{2}\left(\frac{T_0 t}{\Phi_{20}}\right)^2\right) + o(t) \quad , \qquad (7)$$

where $o(t)$ is a low amplitude undesirable term. It is possible to evaluate the broadening factor as the relation between the input and output pulse standard deviation, which is given as

$$\frac{\sigma_{out}}{\sigma_{in}} = \frac{\Phi_{20}}{T_0^2} \quad . \qquad (8)$$

Now, in order to show the numerical results and to analyze the performance of the system, we have considered two input signals: the first one is given by a gaussian pulse, and the second one is given by a super-gaussian pulse, where $m = 3$ was selected. Figure 3 (a) and (b) show the gaussian and super-gaussian input signals, respectively, where $C = -6$ and $T_0 = 16.67$ ps were selected. Can be observed that the super-gaussian pulse shape have a steeper leading and trailing edges. Same as in previous section, we have selecting $\phi_{20} = 10^{18}$ Hz^2 for the phase modulation factor of the EOM. Thus, the dispersion factor for getting the pulse compression, from Eq. (3), is $\Phi_{20}^{(p)} = 46.294$ ps^2.

Figures 3 (c) and (d) show the output intensities obtained when the input signals become a gaussian and a super-gaussian envelope, respectively. It can be observed a temporal pulse compression effect and an increasing of the energy level signal for both input signals. However, this last effect is more noticeable for the case of a gaussian input. The broadening factor, calculated fron Eq. (8), results to be 0.1667 and the amplification intensity level becomes 1.5. Figures 3 (e) and (f) show the pulse time evolution when it is propagated through the dispersive line. In each figure it can be clearly observed the dispersion value for which the pulse compression effect is reached. Besides, it can be seen the formation of an undesired secondary pulse of lower amplitude which is given by the term $o(t)$ in Eq. (7).

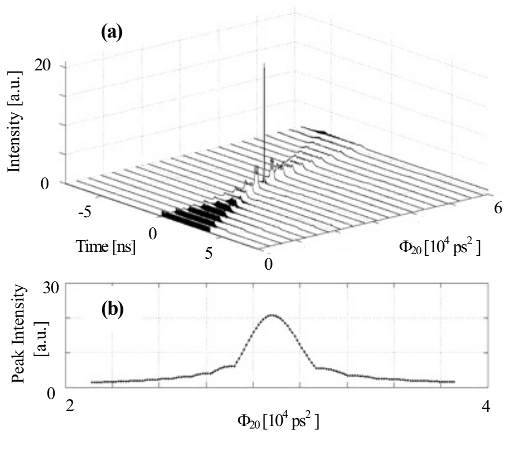

Fig. 2. (a) Three-dimensional display of the output optical power, corresponding to the EOM of Fig. 1(c), which is obtained for a continuously varying Φ_{20}. The high energy pulse conformation is achieved in a well defined condition. (b) Dependence of the maximum output intensity with the dispersion parameter.

V. CONCLUSIONS

In this work we have analyzed a simple technique for compressing optical pulses, by properly combining dispersive propagation and phase modulation. The system performance was illustrated with some numerical simulations. The effect of both, the time lens aberrations and a possible variation of the amount of required dispersion, were analyzed and illustrated. The deviations of the ideal conditions were also considered by introducing the action of real electro-optical modulators and by choosing an input signal that resembles the pulse emission of most semiconductor lasers. The proposed technique of pulse compression can be applied for minimizing intersymbol interference (ISI) in high speed communication systems and for obtaining a TDM channel with a large transmission rate.

ACKNOWLEDGEMENTS

This work was supported by Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET- PIP 6156/05), Facultad de Ingeniería de la Universidad Nacional de La Plata (UNLP - Project I106) and Agencia Nacional de Promoción Científica y Tecnológica (ANPCyT - PICT 38289). PACC is fellowship of CONICET.

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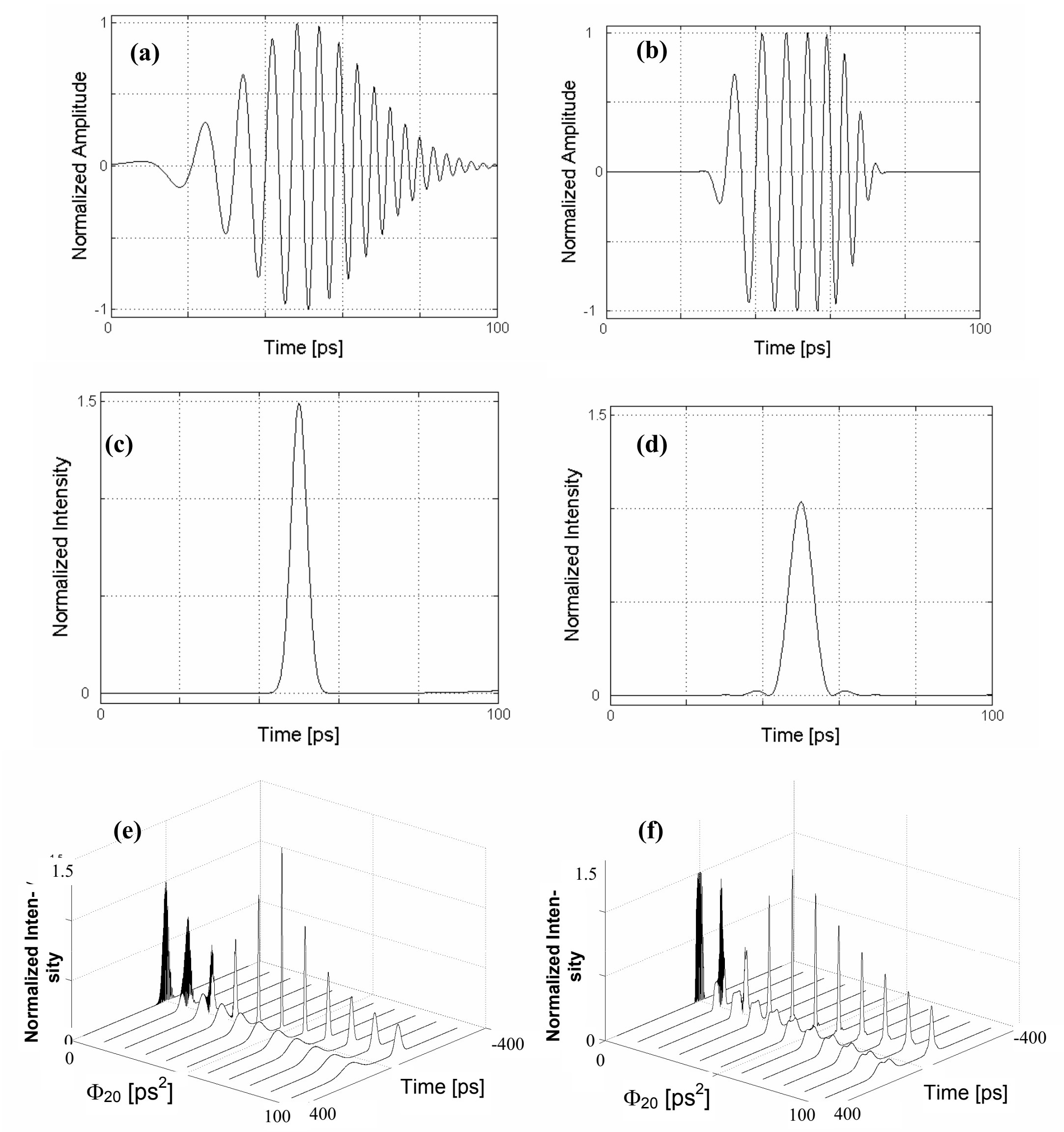

Fig. 3. Typical characteristics of the input and output pulses: (a) and (b) normalized input amplitude for: a gaussian and a super-gaussian chirped pulse, respectively; (c) and (d) normalized output intensity when the condition given as in Eq. (3) is satisfied; (e) and (f) pulse conformation evolutions.

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Received: October 18, 2007.
Accepted: February 26, 2009.
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