Controlling the velocity of ultrashort light pulses in vacuum through spatio-temporal couplings: supplementary material

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This document provides supplementary information to “Controlling the velocity of ultrashort light pulses in vacuum through spatio-temporal couplings,” https://doi.org/10.1364/optica.4.001298. The aim of this document is to establish the experimental feasibility of the control scheme presented in the main text by presenting an actual optical system that could be used to implement it. Applying an adjustable temporal chirp on the laser beam is not an issue, as many different optical systems are now available to this end. The only potential experimental challenge is thus the application of a chosen PFC on the beam. We therefore describe here the design of a convenient and realistic optical system to do so.

1. INTRODUCTION

We first emphasize that PFC can in principle be induced by focusing the beam with a simple chromatic lens. The same optical element is then responsible for both inducing the desired PFC and focusing the beam, and this can have several drawbacks. First, once the numerical aperture of the focusing optics has been fixed (generally imposed by the physical effects that one wants to induce at focus), the only control parameter available to adjust the induced PFC is the constituting optical glass of the lens. This leaves a rather limited flexibility on the choice of the PFC value. Second, from a practical point of view, lenses are often inadequate for focusing ultrashort laser beams, in particular in experiments involving high-peak powers or extremely short pulse durations (e.g. few cycle pulses).

We therefore rather describe a configuration that decouples the application of PFC on the beam from its focusing, while still remaining simple and realistic. We propose the use of an optical system based on the combination of two lenses that induces a chosen value of PFC -in other words, a ‘chromatic doublet’. We have designed this system for beam parameters typical of present 100 TW Ti:Sa femtosecond systems: beam diameter 80 mm (FWHM in intensity for a Gaussian beam), pulse duration 25 fs, central wavelength 800 nm. The doublet is intended to be placed into the collimated beam prior to the focusing optics (typically an off-axis parabola), either before or after temporal compression (depending on the laser peak power).

2. CONSTRAINTS OF THE DESIGN

The constraints that we have imposed for this design were the followings:

- The induced PFC (as defined in the main text) is $\tau_p = 100$ fs. This corresponds to $\tau_p / \tau_F = 4$, which is appropriate to induce the sliding focus effect.

- The doublet has an infinite focal length (i.e. it is afocal) at the central laser wavelength. One can then easily show that for $\tau_p / \tau_F = 4$, the focal length of the doublet for other wavelengths in the laser spectrum is in the kilometer range. In such a way, the doublet can be moved in and out of the beam without significantly affecting the divergence at any wavelength, which makes it possible to easily compare the outcome of experiments with and without the sliding focus effect.

- The doublet does not induce any other significant aberration on the beam. In particular, spherical aberrations are negligible for all wavelengths in the laser spectrum.

- One lens is plano-convex (lens 1: one face with infinite radius of curvature, the other with $R_1 > 0$), and the other is plano-concave (lens 2: one face with infinite radius of curvature, the other with $R_2 < 0$).
curvature, the other with \( R_2 < 0 \). Using two flat surfaces reduces the fabrication cost and facilitates the assembly of the doublet (see below).

3. DEGREES OF FREEDOM

The goal of the design is to determine the parameters that make it possible to fulfill all these constraints, with the following degrees of freedom:

- the radii of curvature \( R_1 \) and \( R_2 \) of the curved faces of lenses 1 and 2,
- the thicknesses \( e_1 \) and \( e_2 \) of these two lenses,
- the distance \( d \) between the lenses,
- the nature of the optical glasses for lenses 1 and 2, with optical indices \( n_1 \) and \( n_2 \) at the central laser wavelength.

The first stage of the design involves analytical and numerical calculations (carried out using Mathematica), and the second one ray-tracing simulations using ZEMAX.

4. FIRST STAGE OF THE DESIGN

In the first stage, we first use the ABCD formalism to calculate the effective focal length of the doublet at the central wavelength, as a function of \( R_1, R_2, e_1, e_2, d, n_1, n_2 \). This analytical calculation shows that once all other parameters are fixed, \( R_2 \) can be adjusted to set this focal length to infinity. We note that getting a lens of arbitrary surface curvature from optical manufacturers can be complicated and costly. Alternatively, one can use the distance \( d \) as an additional adjustment parameter, which allows to fine tune \( R_2 \) to one of the manufacturers’ test plates.

Next, we use geometrical optics to calculate the propagation angle \( \theta \) of beams emerging from the doublet, as a function of their initial distance \( h \) from the optical axis, and make a Taylor expansion of this expression with respect to \( h \). For an infinite focal length, the first order term (in \( h \)) cancels, while the second order term (in \( h^2 \)) is always zero due to axial symmetry. The third order term (in \( h^3 \)) corresponds to spherical aberrations. A calculation of this term as a function of \( n_1 \) and \( n_2 \) shows that it is minimized when \( n_1 = n_2 \). In the rest of the design, we will therefore use the additional constraint \( n_1 \approx n_2 \) as the central laser wavelength. This sets a constraint on the choice of the optical glasses 1 and 2.

Finally, we numerically calculate the spatially-varying spectral phase \( \phi(\omega, h) \) accumulated in the doublet along the optical path of each ray, as a function of its initial distance \( h \) from the optical axis. From this function, we can calculate the pulse front curvature induced on the beam, for any choice of glasses for lenses 1 and 2. The calculation shows that this system can be designed to induce either a positive or negative PFC. We can then use this program to determine which choice of glasses leads to the targeted PFC, and thus finalize the design of the doublet.

Given that \( n_1 \approx n_2 \) at the central laser wavelength, the key remaining parameter in this calculation is the difference between the group indices of the two glasses, which needs to be large enough. Choosing the two glasses is generally insufficient to set the PFC to the desired value. Once the most suitable combination of glasses has been found, we therefore use the radius of curvature \( R_1 \) as an additional tuning parameter, and then recalculate \( R_2 \) and \( d \) as explained above.

5. SECOND STAGE OF THE DESIGN

In the second stage of the design, we use ZEMAX to perform a more accurate calculation of the optical properties of the system in order to validate the parameters provided by the first stage, and slightly adjust these parameters if necessary. The outcomes of this study, for the parameters specified above, are provided in Table S1, together with a sketch of the optical system in Fig. S1.

![Fig. S1. Optical layout of the chromatic doublet. A few typical rays calculated by ZEMAX are displayed in blue.](image)

| Physical parameter | Value       |
|--------------------|-------------|
| \( R_1 \)          | 298 mm      |
| \( R_2 \)          | 291 mm      |
| \( d \)            | 1.03 mm     |
| Glass 1            | S-TIM2 (Ohara) |
| Glass 2            | N-PSK53A (Schott) |

Table S1. Physical parameters of a ‘chromatic doublet’ that induces a PFC \( \tau_P = 100 \) fs on a 80 mm diameter beam centered at 800 nm.

The thicknesses of lenses 1 and 2 do not have any significant effect, and are therefore not specified. After this doublet, the femtosecond laser pulse has a time advance on the edges of the beam, with respect to the center. As a result, after a subsequent focusing optics, the larger wavelengths are focused further away along the optical axis.

The performances of the system are summarized in Fig. S2 and S3. Fig. S2 shows the optical power \( (1/f \) with \( f \) the focal length) of the doublet as a function of wavelength, which varies quasi-linearly -as explained in the main text, this is a signature of the PFC induced on the beam after the optical system. Fig. S3 shows the spot diagram (dots) calculated with ZEMAX for three different wavelengths across the laser spectrum, at best focus for each wavelength. In all cases, all rays are well inside the Airy radius (full line), which indicates the absence of any significant geometrical aberrations at these three representative wavelengths.
Fig. S2. Variation of the optical power with wavelength, calculated by ZEMAX.
Fig. S3. Spot diagram calculated by ZEMAX after the chromatic doublet and a perfect focusing optics, at three wavelengths (750, 800, 850 nm, from top to bottom) and at the best focus of each wavelength. The circles in full line show in each case the Airy radius corresponding to the diffraction limit.