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SHORT COMMUNICATION

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Phase compensation scheme to achieve clean pulses from a multipass cell post-compression setup

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Abstract. An effective post-compression scheme requires a good compression system to generate the desired ultrashort pulse. In this work, we demonstrate that a compressor based on a pair of grisms, with an additional piece of dispersive glass, is able to shorten pulses coming from an all-bulk multipass cell post-compression setup to temporal profiles very close to the transform limited one. This proposal paves the way for the design of compressors, not based on chirped mirrors, with excellent performance.

Keywords: Multipass cells, Nonlinear propagation, Post-compression.

1 Introduction

The fast development of intense ultrashort laser pulses has promoted remarkable scientific fields such as ultrafast optics, attosecond science and microscopy [1–4]. To improve the temporal and spatial resolution of the experiments the scientific community demands even shorter, more intense and better-quality pulses. These ultrashort pulses are usually obtained by means of post-compression schemes in which the pulse spectrum is first broadened, due to Self-Phase Modulation (SPM) and other nonlinear effects, and second, the spectral phase is compensated to obtain an output as close as possible to the transform limited pulse [5, 6]. The second step can be skipped, if we are able to develop the spectral broadening step in the self-compression regime, in which the pulse shortens its temporal duration while broadening its spectrum [7, 8].

Among the diverse two-step post-compression schemes used to perform this spectral broadening, multipass cells (MPCs) have emerged as a strong option due to their reliability and versatility [8, 9]. MPCs are cavities formed by two mirrors in which a laser beam is propagated several round trips, broadening its spectrum by introducing some nonlinear media that could be a gas filling the cell, or one or several solid plates. Solid nonlinear media-based MPCs have some advantages over the gas-filled ones since they have higher nonlinearity and a simpler setup. One way to successfully perform this spectral broadening in a smooth and controlled way is to work in the enhanced frequency chirp regime (EFCR), a regime in which the material dispersion and the nonlinearity act together achieving a broad and relatively smooth spectrum compatible with a very clean and short temporal profile, after passing through an adequate compression system. The EFCR has been already described in MPCs filled with gases [10–12] and with solid plates [13].

As mentioned above, after the propagation through the MPC, where the spectrum has been broadened, it is necessary to compress the pulse. A good compression stage is essential to obtain the desired short and clean pulses and, therefore, has been largely studied in the literature, where the most common approaches are gratings, chirped mirrors or grisms (diffraction gratings written on a prism) [14–17]. One of the most limiting parts of these compressors, when dealing with pulses with single or few optical cycle durations, are the chirped mirrors, widely used in these cases. Standard chirped mirrors present limited spectral bandwidth and, moreover, they focus on compensating the group delay dispersion (GDD), but here we will be also interested in compensating higher order dispersion terms. We show here, by means of numerical simulations, a new compressor setup, without chirped mirrors, able to obtain short, clean intense pulses for the case of an all-bulk MPC post-compression system. This compressor, based on a pair of grisms and the addition of some material dispersion, compensates very well the phase coming out of the MPC, even in the case of few-cycle pulses. We have been able to find a compressor configuration which allows us to obtain pulses that are very close to their Fourier Limit regarding duration, cleanness and peak intensity.

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2 Material and methods

Recent studies demonstrate that a MPC post-compression setup working in the EFCR is an excellent candidate to generate clean short pulses. This scenario has been discussed theoretically in gas-filled MPCs [10, 11] and in an all-bulk setup [13], and demonstrated experimentally in gas-filled MPCs [12]. All these works demonstrate that the spectral phase obtained after the spectral broadening process is smooth but not as simple as one would desire, showing high order terms (mostly even contributions). Therefore, we need to find a compressor setup with enough degrees of freedom to be able to compensate this spectral phase without using chirped mirrors. A compressor consisting of a pair of grisms could be a good solution to start with.

To reach these spectrally broadened non-compressed pulses, we simulate the propagation of the pulses in the MPC in the EFCR. In this case we have focused on an all-bulk MPC system, which we believe is the most complex and extreme situation. We will take advantage of previous simulation results recently obtained in all-bulk MPC setups in the EFCR [13]. These simulations are done using a standard split-step Fourier method including both the linear effects – diffraction and dispersion – and the main nonlinear effects: SPM, self-steepening and Raman effects. A complete description of the numerical strategy can be seen in [11]. Our first attempt will be with the output pulse obtained when introducing a pulse centered at 800 nm, with 220 μJ and 150 fs pulse duration (half width at $1/e^2$ of the intensity distribution) into an MPC with two identical concave mirrors separated 40 cm. We assume that the beam is perfectly coupled to the fundamental mode of the cavity with a waist of 500 μm. The cavity is vacuum-sealed, and we add two thin fused silica plates 500 μm thick placed at the cavity mirrors as nonlinear media. After the pulse travels through the cell during 40 round trips the output on-axis intensity distribution doubles the temporal duration of the input one, but with a much broader spectrum, being compatible with a very clean Transformed Limited Pulse (TLP) of 20.7 fs full width at half maximum (FWHM) and with temporal sidelobes below 0.3% of the TLP peak intensity. The spectral phase of the output spectrum on-axis is quite smooth with a big quadratic component but, as described in [13], also with other relevant even components.

To achieve the phase compensation of this output pulse (case I) we will design a compressor based on a pair of grisms. In our case, we have simulated a grism compressor following the phase response described in [18]. Although a system based on a pair of grisms compensates fairly well the phase of the output pulse, we will demonstrate that we can improve the setup by introducing a piece of dispersive material, as shown in Figure 1. We have, therefore, developed a multivariable optimization of the compression process taking into account eight tuning parameters: the angle of the prism apex (α_Δ), the angle of incidence (θ_{in}), the entrance position in the grism (L_{in}), the grisms separation (L_{GRISM}), the tip-to-tip distance of the prisms (L_{tip}), the diffraction grating density (C_{Grating}), the material used

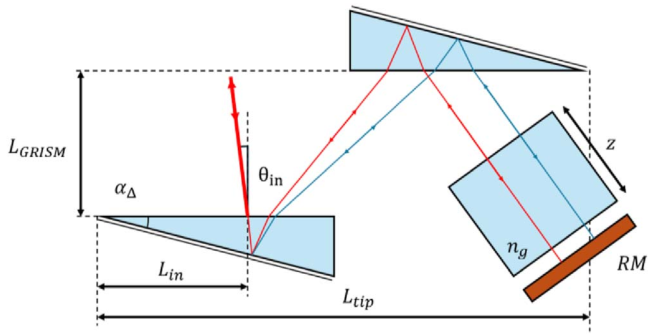

Figure 1. Compressor scheme based on a pair of grisms and a piece of glass.

for the extra piece of glass, with a particular refractive index (n_g), and its thickness z. For both the prisms and the piece of glass, we have used SF10 as the material, for which we use the Sellmeier coefficient to simulate the complete dispersion curve [19]. The optimization is done by looking for a compressed pulse with the highest peak intensity, as close as possible to the TLP peak intensity, while doing the scan over all the compressor parameters enumerated above.

3 Results and discussion

Figure 2a shows the compressed pulses obtained with the grism-only approach (red line) and with the grism with a 46.5-mm thick SF10 plate added in the setup (green line), both compared with the TLP (blue line). As can be observed, the grism-only compressor is enough to successfully shorten the pulse to almost the same temporal duration as the TLP, with an intensity peak that reaches 83% of the TLP peak intensity, but showing side lobs as intense as 4.73% of the pulse peak intensity. The configuration of the compressor that yields this compressed pulse is detailed in the first row of Table 1. As can be observed it does not include any extra piece of glass (z).

If we introduce an additional piece of glass (SF10 in this case) before the retro-reflecting mirror (RM), it is possible to perform a better compression of the pulse, reaching 95.87% of the peak intensity of the TLP and showing side lobs with a maximum intensity value of 0.59% of the pulse peak intensity. The configuration of this new compressor proposal is detailed in the second row of Table 1. Adding the piece of glass in the setup notably improves the performance of the compressor since we introduce an additional degree of freedom to optimize the compression process.

To check if this combined compressor setup is also valid to achieve clean few-cycle pulses we can use the output pulse coming out of the third compression stage proposed in [13]. In that case the on-axis output spectrum obtained corresponds to a 3.88 fs FWHM TLP, with sidelobes reaching 0.03% of the TLP peak intensity. Figure 2b shows the compressed pulses obtained with the grism-only approach (red line) and with the grism with a 3.55-mm thick SF10 plate added in the setup, both compared with the TLP

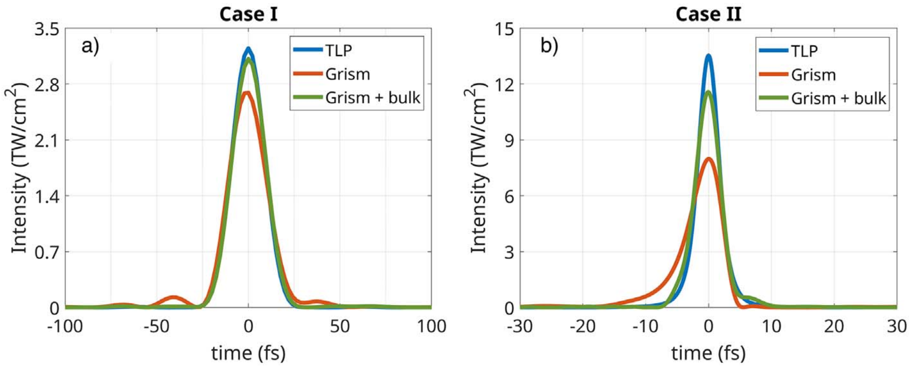

Figure 2. Intensity distribution of the TLP (blue line) for case I (a) and case II (b), showing the compressed pulse using a grism-only compressor (red line) and the compressed pulse with an additional SF10 glass piece to the grism pair (green line), with configurations described in Table 1 (rows 1–2 for case I, rows 3–4 for case II).

Table 1. Parameters for the grism and grism + glass compression systems used for the two pulse compression cases described in the text. Values are given for the prism angle (α_Δ), input grism angle (θ_{in}), incident depth (L_{in}), grisms separation (L_{GRISM}), grism tip-to-tip distance (L_{tip}), grating density ($C_{Grating}$) and the SF10 slab thickness z.

System	α_Δ (°)	θ_{in} (°)	L_{in} (mm)	L_{GRISM} (mm)	L_{tip} (mm)	$C_{Grating}$ (lines/mm)	z (mm)
Grism (case I)	14	7	85	62	220	1000	–
Grism + glass (case I)	15	7	14	71	251	1100	46.5
Grism (case II)	30	16	15	30	0	1000	–
Grism + glass (case II)	10	22	35.5	8.5	7	450	3.55

for this new case (case II). On one hand, the grism-only compressor shortens the pulse showing a relatively clean profile but with a slightly longer temporal duration than the TLP. In this case, the pulse reaches a peak intensity that is 58.96% of the TLP peak intensity, showing side lobs as intense as 1.05% of the pulse peak intensity. The configuration of the compressor that yields this pulse is detailed in the third row of Table 1. On the other hand, the grism + glass compressor setup shows a much better performance, achieving a compressed pulse reaching 85.48% of the peak intensity of the TLP and showing side lobs with a maximum intensity value of 0.47% of the pulse peak intensity. The configuration of this new compressor proposal is detailed in the fourth row of Table 1.

4 Conclusion

We have demonstrated that a compressor based on a pair of grisms with the addition of a piece of glass is a very good option to achieve clean ultrashort post-compressed pulses from an all-bulk MPC post-compression setup. We have shown that this setup works for pulses both in the multi-cycle and few-cycle regimes, and we have also verified that the introduction of a piece of glass in the compression setup notably improves the cleanness of the compressed pulse.

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Conflicts of interest

The authors have nothing to disclose.

Data availability statement

Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

Author contribution statement

J.S.R and E.C.J: Conceptualization, methodology and supervision. V.W.S.S.: Software, validation and formal analysis. All the authors contribute to writing and preparing the original draft, review and editing. J.S.R.: Fund acquisition.

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