Generating clean few-cycle pulses in an all-bulk multipass cell scheme

Víctor Wilfried Segundo Staels[1,*], *Enrique* Conejero Jarque[1,2], and *Julio* San Roman[1,2]

[1]Grupo de Investigación en Aplicaciones del Láser y Fotónica, Departamento de Física Aplicada, Universidad de Salamanca, E-37008, Salamanca, Spain

[2]Unidad de Excelencia en Luz y Materia Estructuradas, Universidad de Salamanca, E-37008, Salamanca, Spain

Abstract. We theoretically demonstrate the generation of clean few-cycle pulses in a three-stage all-bulk multipass cell scheme. By meticulously selecting the number of round trips and the width of the material used in each cell, we are able to keep the three stages in the enhanced frequency chirp regime. The results show the generation of short and clean pulses, with compression factors approaching 50 with a final duration below 1.5 cycles.

1 Introduction

The generation of short, well-shaped laser pulses holds great importance in the fields of ultrafast optics and attoscience [1]. Usually, this type of pulses is obtained in a post-compression stage where the original pulse broadens its spectrum through nonlinear optical effects, with self-phase modulation (SPM) emerging as the most efficient phenomenon. After that, in a second stage, the spectral phase is compensated so that the final pulse approaches its Fourier limit [2]. Initially demonstrated in optical fibers, this technique has been extended to hollow core fibers and photonic crystal fibers, where it has become widely adopted. More recently, the introduction of Multipass Cells (MPCs) as a post-compression tool has gathered attention. MPCs, composed of two mirrors forming a cavity, enable the semi-free-space propagation of pulses, facilitating pulses with high energy and excellent spatial quality [3,4]. To generate short pulses with very clean temporal profiles, it has recently been proven that the Enhanced Frequency Chirp Regime (EFCR) within MPCs filled with gas is an interesting strategy [5–7]. In the EFCR, smooth spectral broadening occurs due to the complex balance between the two primary propagation effects: dispersion and SPM, enabling the generation of short and clean pulses as long as the compression stage is good enough.

In this contribution, we explore the compression of short pulses within an all-bulk MPC scheme propagated in the EFCR by means of numerical simulations. We demonstrate that this scheme can be taken to the limit to generate clean few-cycle pulses by properly designing three consecutive MPC stages.

2 Results and discussion

It is well-known that to enter the EFCR we need to be in a situation where the dispersion effects and the nonlinear interaction are both important. In terms of the fundamental lengths of the process, the EFCR condition to be fulfilled is: $L_{NL}<L<L_D$ [7] where L, L_{NL} and L_D represent the total material width, the nonlinear length and the dispersion length, respectively (the definition of the latter two can be found in [8], for example). When using a bulk material, as is the case, there are other issues to consider, as the nonlinear propagation is much more intense than in lower density materials. First, the input pulse at the entrance of the propagation must have a smooth temporal profile with no pre-pulses or post-pulses. If this is not the case, this structure will cause the amplification of the lower and higher frequencies of the spectrum and the pulse will exit the Enhanced Frequency Chirp Regime. The other restriction will be to keep the glass propagation distance below the collapse distance to avoid entering an exceedingly high nonlinear interaction regime. All these restrictions will favour the propagation in the EFCR, thereby aiding to keep a smooth spectrum, which leads to short and clean temporal shaped pulses.

As an example of EFCR, we have simulated the propagation of a Gaussian pulse of 177 fs at full width at half maximum (FWHM) and 220 µJ centred at 800 nm into a first stage formed by a 40 cm long Multipass cell. This MPC is vacuum-sealed and has two fused silica glasses of 500 µm placed at the mirrors which will act as nonlinear media. We mode match the beam at the entrance of the cavity to a 500 µm waist and we let the pulse propagate 40 round trips, making a total of 32 m of propagation inside the cell and 80 mm through glass.

---

[*] Corresponding author: vwsstaels@usal.es

In these circumstances, the pulse propagates in the EFCR, broadening its spectrum and reaching an output pulse whose transform limit has a duration of 20.74 fs (FWHM). To shorten even more the pulse, we use another stage after compressing, at least partially, the output pulse of the first one. If we take the output pulse and compensate its phase up to its fourth order obtaining a 21.51 fs FWHM, we could introduce the pulse into another MPC cell with adapted configuration to make sure we continue to fulfil the propagation lengths restriction. Using the same 40 cm cavity, we now need 100 µm of glass placed at the mirrors and only 5 round trips to reach a second pulse with 7.14 fs FWHM transform limited duration.

We can repeat this process a third time with a single pass through a 150 µm glass and finally reach a pulse with a transform limit FWHM duration of 3.68 fs, which corresponds to a total compression factor of 48.

The selection of the number of roundtrips and the width of the bulk material used in each stage has been done so that the condition on the fundamental lengths is always fulfilled, as shown in figure 1 (Top). For this reason, the total propagation length in the multipass cell has to be shorter in each stage due to the reduction of the pulse duration and the increasing peak power.

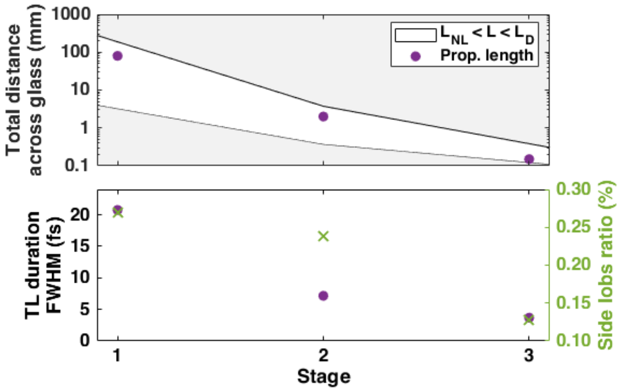

Fig. 1. (Top) Total glass propagation length through the three different stages. The white area represents the region within the limits of nonlinear and dispersion lengths. (Bottom) Evolution of the transform limited (TL) pulse duration (bottom left) together with the intensity ratio of the maximum satellite intensity and the main peak intensity (bottom right).

In figure 2 we show the transform limited end pulse outcoming from the third stage together with the pulse retrieved when compensating for the spectral phase up to fourth order. After this compensation, we retrieve a pulse with a FWHM duration of 3.92 fs, which is close to the duration of the transform limited pulse.

The output pulse has a clean shape without remarkable side structures. In fact, the ratio between the maximum intensity of the side lobs and the maximum intensity of the centre structure is only 0.13 % at the output pulse. The evolution of this ratio along the three consecutive stages can be seen in the bottom panel of figure 1, together with the evolution of the duration of the transform limited pulse.

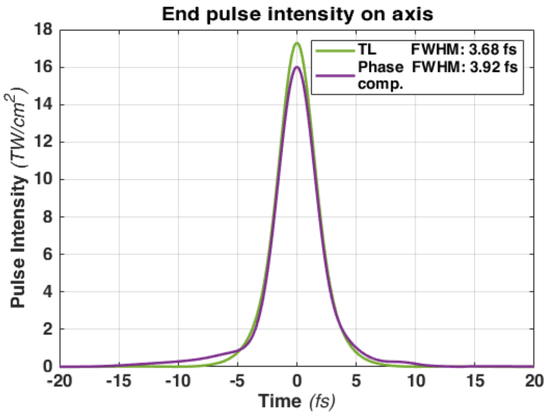

Fig. 2. Output transform limited pulse temporal profile (green) and the retrieved pulse when phase is compensated up to forth order (purple).

3 Conclusions

In this numerical investigation, we show that meticulous parameter selection enables clean short temporal pulses with compression factors close to 50. These pulses are obtained after propagation in three consecutive multipass cell stages filled with bulk media within the Enhanced Frequency Chirp Regime. These results pave the way to obtain clean ultrashort optical pulses useful for applications in attoscience and ultrafast optics.

This work was supported by: PID2022-142340NB-I00, funded by the Spanish Ministry of Science and Innovation, and PRE2020-092181, funded by the Ministry of Economy and Competitivity.

References

1. P. B. Corkum and F. Krausz, Nature Phys **3**, 381 (2007).
2. T. Nagy, P. Simon, and L. Veisz, Advances in Physics: X **6**, 1845795 (2021).
3. M. Hanna, F. Guichard, N. Daher, Q. Bournet, X. Délen, and P. Georges, Laser & Photonics Reviews **15**, 2100220 (2021).
4. A.-L. Viotti, M. Seidel, E. Escoto, S. Rajhans, W. P. Leemans, I. Hartl, and C. M. Heyl, Optica **9**, 197 (2022).
5. M. Benner, M. Karst, C. Amaya Mendez, H. Stark, and J. Limpert, J. Opt. Soc. Am. B **40**, 301 (2023).
6. M. Karst, M. Benner, P. Gierschke, H. Stark, and J. Limpert, Opt. Lett. **48**, 5899 (2023).
7. V. W. S. Staels, E. C. Jarque, D. Carlson, M. Hemmer, H. C. Kapteyn, M. M. Murnane, and J. S. Roman, Opt. Express, OE **31**, 18898 (2023).
8. G. P. Agrawal, Fifth edition (Elsevier/Academic Press, 2013).