Supercontinuum generation in the enhanced frequency chirp regime in multipass cells

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Abstract. We identify, via numerical simulations, the regime of enhanced frequency chirp during nonlinear propagation in multipass cell. This regime - used before the dawn of chirped pulse amplification to generate ultrashort pulses - paves the way for the generation of temporally clean few-cycle pulses. Here, we demonstrate numerically that the spectra of pulses from an Yb-based laser system can be broadened into a flat supercontinuum with a smooth spectral phase compatible with a clean few-cycle pulse with temporal secondary structures with peak intensity below 0.5% that of the main peak.

1 Introduction

A limited number of laser systems - such as Ti:Sapphire or Cr:ZnSe - feature emission bandwidths that support the direct generation and amplification of ultrashort pulses. Other laser gain media - such as most rare-earth doped material - feature advantageous spectroscopic (enabling direct diode pumping) or thermo-optic properties (enabling high average power operation) but fail to provide emission spectra supporting ultrashort pulses. In order to derive ultrashort pulses from such systems, nonlinear post-compression schemes must be implemented. In the early 80s, the nonlinear propagation of laser pulses through optical fibres was proposed to compress optical pulses in the anomalous [1] and normal dispersion regimes [2]. This scheme was adapted in 1996 to compress ultra-intense laser pulses by using hollow-capillary fibres [3] or photonic crystal fibres [4], which are the most used post-compression schemes nowadays. However, these schemes have some intrinsic limitations related to propagation losses, damage threshold, fiber length and pulse energy that set an upper limit on practical energy scaling capabilities. For these reasons, new and complementary nonlinear compression methods have been investigated to enable operation in regimes of input pulse parameters where hollow-fibers become impractical. One of these schemes is nonlinear propagation of optical pulses in multipass cells (MPC) [5,6]. MPCs are cavities formed by two mirrors, typically filled with a noble gas or containing a thin dielectric plate in which a laser pulse propagates several roundtrips. During this propagation, the pulse experiences nonlinear propagation yielding spectral broadening while self-focusing is mitigated by the resonating nature of the propagation. In order to obtain clean short pulses, we propose to propagate the pulse in a gas-filled MPC in the same enhanced frequency chirp regime used with optical fibers in the 80s [2]. In this regime, the spectrum is broadened to a smooth spectral shape and phase - contrary to the typically strongly modulated spectra obtained via SPM.

In this work we use numerical simulations to investigate the enhanced frequency chirp regime in MPCs and identify the most promising parameter sets to achieve broad and clean spectra for experimentally relevant input pulse parameters.

2 Numerical Model

To simulate the propagation of a laser pulse in the gas-filled MPC we use a (3+1)D model [7], including the three spatial and temporal dimensions. We apply the Split-Step Fourier Method to propagate the envelope of the pulse accounting for diffraction, dispersion, SPM, self-focusing and self-steepening. We neglect the Raman effect contribution since our simulations are performed in monoatomic gases, as well as the ionization since we ensure the peak intensities involved remain below the ionization threshold. We also assume that the mirrors of the MPC have negligible dispersion. The spatio-temporal window has a minimum grid of $128 \times 128 \times 512$ points and is defined so that the beam perfectly fits during the entire propagation in the MPC.

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3 Results and discussion

In order to delimit the region in which the enhanced frequency chirp regime in MPCs occurs, we impose the following three conditions: (i) the maximum peak power must remain below the critical peak power to prevent self-focusing; (ii) $L_{NL} < L < L_D$ and (iii) $1 < N = \sqrt{L_D/L_{NL}} < 20$, where L is the total propagation length in the MPC, L_{NL} is the nonlinear length and L_D is the dispersion length as defined in [8]. To find the region in which these conditions are fulfilled, we simulate 20 roundtrips of a Yb-based pulse with a duration of 177 fs at full width half maximum (FWHM) centred at 1030 nm in a 40 cm confocal cavity filled with argon. With these fixed parameters, we perform a gas pressure and pulse energy scan looking for the region in which the enhanced frequency chirp regime is optimum for the generation of a smooth supercontinuum, which we find around 10 bar and 100 μJ. In this region of parameters, the nonlinearity generates an important spectral broadening, mainly due to SPM, while the linear and nonlinear dispersion contribute to temporally stretch the pulse so that the spectrum losses its characteristic SPM modulations and acquire a quite smooth profile. Moreover, the beam presents a very good spatial homogeneity as it is well known for MPCs systems.

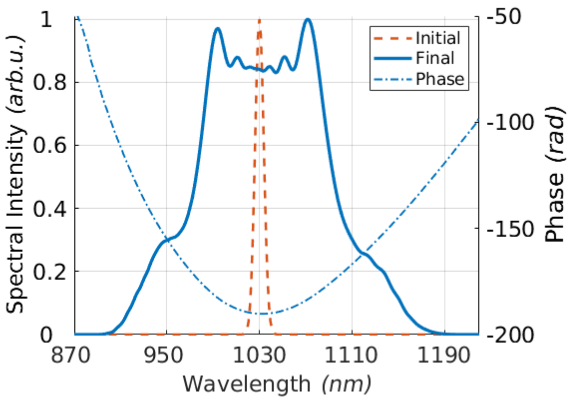

Fig. 1. Input (dashed red) and output (solid blue) on-axis spectral intensity profiles of a 100 μJ, 177 fs FWHM pulse in a confocal cavity filled with 10 bar of argon. The dashed-dotted line represents the output spectral phase.

Figure 1 shows the input and the output on-axis spectra, together with the spectral phase of the output spectrum for the case of 10 bar of argon and a pulse energy of 100 μJ. The broadened spectrum presents a relatively flat structure with a FWHM of 116 nm (~205 THz). The spectral phase presents a smooth, parabolic-like behaviour, as expected in this regime. The output spectral shape allows a temporal transform limited pulse of 14 fs FWHM (a compression factor >12) without visible sidelobes (less than 0.5% of its peak intensity). The input and output temporal pulses together with the transform limited output pulse are shown in figure 2. For better comparison, the transform limited output pulse shown in figure 2, which has a peak intensity of 2.8 $\mathrm{TW/cm^2}$, has been normalized to the same peak intensity as the input pulse.

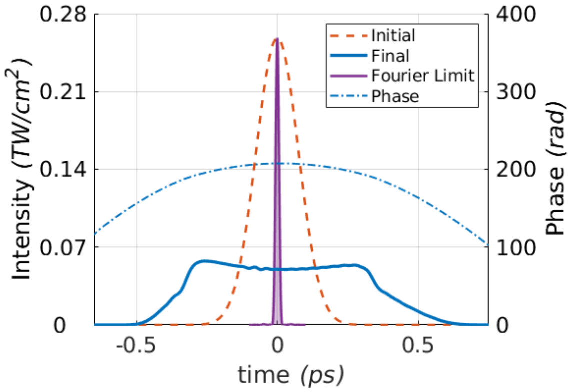

Fig. 2. Input (dashed red) and output (solid blue) on-axis temporal intensity profiles corresponding to the spectrum in Fig. 1. The transform limited pulse is plotted in purple and has been normalized to the peak intensity of the input pulse (it reaches a peak intensity of 2.8 $\mathrm{TW/cm^2}$).

4 Conclusion

In this work, we show that it is possible to reproduce the enhanced chirp regime in multipass cells, yielding broad and smooth spectra compatible with clean and ultrashort transform limited pulses. For the case of 20 roundtrips of a Yb-based pulse with a duration of 177 fs at FWHM centred at 1030 nm in a 40 cm confocal cavity filled with argon, this regime appears around 100 μJ and 10 bar and opens a way to obtain clean ultrashort optical pulses.

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References

1. L. F. Mollenauer, R. H. Stolen, and J. P. Gordon, Phys. Rev. Lett. **45**, 1095 (1980).
2. H. Nakatsuka, D. Grischkowsky, and A. C. Balant, Phys. Rev. Lett. **47**, 910 (1981).
3. M. Nisoli, S. De Silvestri, and O. Svelto, Appl. Phys. Lett. **68**, 2793 (1996).
4. J. C. Knight, T. A. Birks, P. St. J. Russell, and D. M. Atkin, Opt. Lett. **21**, 1547 (1996).
5. M. Hanna, F. Guichard, N. Daher, Q. Bournet, X. Délen, and P. Georges, Laser & Photonics Reviews **15**, 2100220 (2021).
6. A.-L. Viotti, M. Seidel, E. Escoto, S. Rajhans, W. P. Leemans, I. Hartl, and C. M. Heyl, Optica **9**, 197 (2022).
7. M. Hanna, X. Délen, L. Lavenu, F. Guichard, Y. Zaouter, F. Druon, and P. Georges, J. Opt. Soc. Am. B, JOSAB **34**, 1340 (2017).
8. A. Couairon and A. Mysyrowicz, Physics Reports **441**, 47 (2007).