Pulse self-compression down to the sub-cycle regime in hollow capillary fibers with decreasing pressure gradients

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Abstract. We theoretically demonstrate an enhancement in the generation of clean, near-infrared sub-cycle laser pulses by soliton self-compression in gas-filled hollow capillary fibers using decreasing pressure gradients. Furthermore, we identify the optimal input parameters for high quality compression and the main advantages of this promising technique which paves the way towards ultrafast vacuum experiments.

1 Introduction

In the last years, pulse post-compression in gas-filled hollow capillary fibers (HCFs) has become a widely used method for generating energetic ultrashort laser pulses [1]. These pulses, with time durations of a few femtoseconds, are now enabling tools for ultrafast time-resolved spectroscopy and strong-field physics driving extreme-ultraviolet high-harmonic generation. Very recently, high-energy soliton dynamics in HCFs arising from the interplay between the negative group-velocity dispersion of the waveguide and self-phase modulation (SPM) have attracted a great interest as a direct route to extreme pulse self-compression down to the few- and sub-cycle regime in the optical spectral region [2, 3]. However, as this interaction can be very complex and dynamic, it is still necessary to identify the optimal experimental parameters for high-quality self-compression [4], and design guidelines are essential.

Some recent studies have suggested the use of decreasing pressure gradients in HCFs to avoid the distortions introduced by the transmission through the output windows and deliver the self-compressed pulses directly to vacuum experiments [5], and to minimize the nonlinear mode coupling and improve the purity of the output beam in the compression of the higher-order spatial modes of these fibers [6].

In this work, we explore further advantages of the negative pressure gradient technique, showing that it can be applied to the self-compression of standard near-infrared (NIR) pulses in the fundamental mode of typical HCFs to generate sub-cycle pulses with shorter durations, higher peak powers and a better temporal structure when compared to those obtained in the equivalent constant pressure situations [7], defined by matching the accumulated nonlinear phase shift, also known as B-integral, along the propagation [8].

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2 Results

To study the nonlinear propagation dynamics of ultrashort pulses in gas-filled HCFs we have numerically solved the one-dimensional generalized nonlinear Schrödinger equation for the pulse envelope in a regime of moderate intensity, including the linear losses of the fiber, the complete dispersion, SPM and self-steepening. To identify the optimal input parameters for obtaining high-quality sub-cycle pulses by soliton self-compression in typical experimental configurations, we have systematically simulated the propagation of a 30 fs pump pulse at 800 nm in the fundamen-

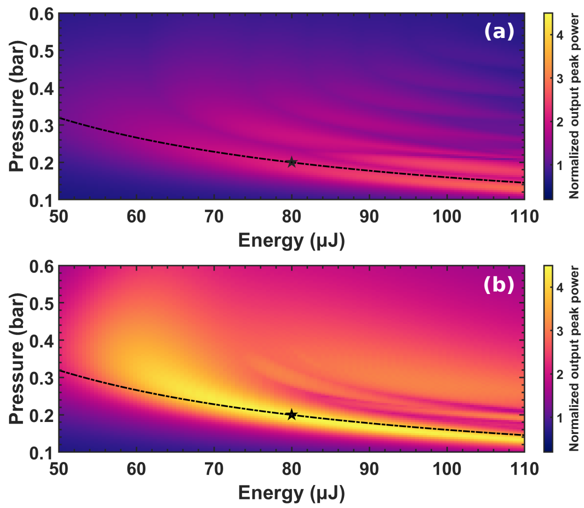

Figure 1. Peak power of the self-compressed pulses normalized to its initial value as a function of input pulse energy and equivalent gas pressure for (a) a statically argon-filled HCF and (b) its equivalent differentially pumped fiber with a decreasing pressure gradient. The dot-dashed line represents the curve of constant B-integral (B = 8.5 rad) which best fits the optimal region for high-quality self-compression and the star refers to the final situation shown in Fig. 2 (80 μJ, 200 mbar).

tal mode of a 3 m long, 100 μm core radius argon-filled HCF with both decreasing and constant pressure. In the parameter space ranging from input pulse energies of 50 to 110 μJ and gas pressures from 100 to 600 mbar, we have found a wide global optimal region for self-compression in the decreasing pressure gradient (Fig. 1). We have also verified that this optimal behavior is not affected by detrimental nonlinear effects such as self-focusing or ionization by comparing the results with a complete 2D propagation model [9].

As we can see in Fig. 1, the decreasing pressure gradient effectively prevents the onset of these higher-order nonlinear effects by shifting the optimal self-compression region towards lower energies when compared to the optimal parameters for constant pressure, which would lie further towards the lower pressure and higher energy corner of the grid. This allows for the generation of high-quality self-compressed pulses even in gases with low ionization potentials, such as argon. We have also demonstrated that with the differentially pumped fiber the optimal parameter region is wider that in the constant pressure case. This represents a clear experimental advantage as it would make the setup more robust against slight deviations from the optimal input parameters.

Furthermore, we have obtained a simple relation between the input pressure and the pulse energy based on the B-integral which allows to place the optimal region for self-compression in the 2D parameter space [7]. One of the output pulses along this curve is shown in Fig. 2, corresponding to the situation depicted with a star in Fig. 1. As we can clearly realize, in this regime the self-compressed

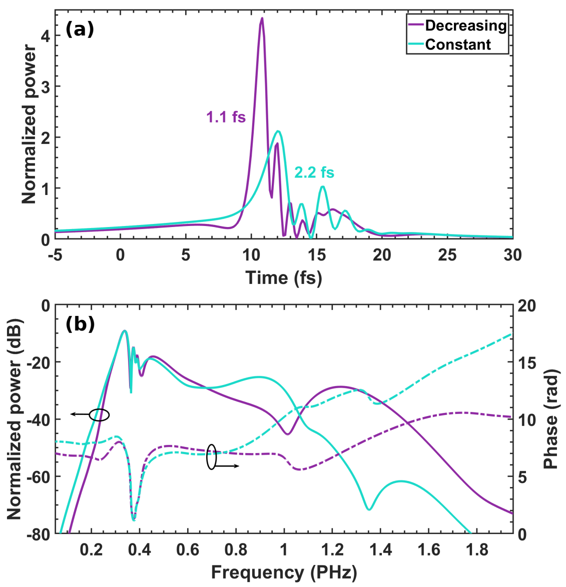

Figure 2. (a) Output pulses and (b) their corresponding spectra obtained after the propagation of a 80 μJ, 30 fs gaussian pump pulse at 800 nm through a 3 m long, 100 μm core radius HCF homogeneously filled with argon at 200 mbar (cyan) and with its equivalent decreasing pressure gradient ending in vacuum (purple). In both plots, the power is normalized to its initial peak value and the labels next to each pulse in (a) stand for the FWHM output durations.

pulses are much better in the decreasing pressure gradient case (purple) as they have shorter durations, higher peak powers and a cleaner temporal structure than those obtained with the equivalent constant pressure (cyan). This improvement is attributed to an effective suppression of higher-order dispersion and self-steepening in the last stages of the pulse compression [6], together with a continuous shift of the zero-dispersion frequency towards higher frequencies at the same time as the pulse spectrum broadens by SPM during its propagation in the fiber. The output pulse obtained from the differentially pumped fiber in Fig. 2(a) reached a sub-cycle full width at half maximum (FWHM) duration of 1.1 fs, corresponding to a peak power of 10.9 GW. Similar results were obtained at other energies and gas pressures lying in the optimal region [7].

3 Conclusions

In conclusion, we have identified the optimum regime to obtain single- to sub-cycle NIR pulses by soliton self-compression in HCFs filled with gas with a decreasing pressure gradient, showing that there is a relative broad region, defined by a simple relation between the input pulse energy and the average gas pressure, where high-quality self-compression can be achieved. In addition to the intrinsic experimental advantage of decreasing pressure gradients to couple the output pulses directly to vacuum experiments, we have also shown that they can considerably improve the robustness of the setup and the quality of the compression process when compared to the equivalent constant pressure situation, also preventing the onset of undesirable nonlinear effects. We believe that these findings will pave the way for a new generation of experiments in time-resolved spectroscopy and attosecond science.

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