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33-fold pulse compression down to 1.5 cycles in a 6m long hollo-core fiber

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Abstract. We demonstrate 33-fold pulse compression employing a 6-m-long hollow-core fiber and chirped mirrors. 1 mJ, 170 fs pulses at 1030 nm are compressed to 5.1 fs (1.5 optical cycles) with 70% efficiency.

1. Introduction

Few-cycle, high-energy optical fields have been a fundamental tool for the investigation of ultrafast and strong-field-driven laser phenomena. However, the direct generation of such optical pulses is still very challenging, since it requires ultra-broadband spectra exceeding the limits of common laser gain media. In particular, Yb-based chirped-pulse amplification systems, an increasingly popular solution for both scientific and industrial applications, are limited to ~200 fs, which in turn hampers their applicability for ultrafast science [1]. In order to support operation in the few-cycle regime, the spectrum of laser pulses can be further extended by means of nonlinear optical effects. In a typical implementation, a laser pulse is spectrally broadened while propagating through a $\chi^{(3)}$ nonlinear medium (Kerr), and is finally compressed by means of linear dispersive elements that remove the nonlinear-induced chirp, as firstly demonstrated in 1969 [2]. In the recent years, various compression schemes have been proposed for pulse energies as low as few hundreds of microjoules, with moderate compression factors in single-pass or high compression factors in multi-pass configurations [3]. Regardless of the technique employed, the common strategy to achieve high compression factors is to drive a “slightly nonlinear” propagation, in order to avoid higher order nonlinear effects and eventually obtain a well-behaved broadening [4]. In this study, we show a simple route to comply with this strategy by using a single-pass gas-filled hollow-core fiber (HCF). By driving the process at a moderate intensity for a long propagation distance, we demonstrate direct 33-fold pulse compression in a single stage, starting from an Yb:KGW regenerative amplifier emitting 170 fs at 1030 nm down to the single-cycle regime (5.1 fs, 1.5 cycles at 1030 nm), by simply using a single argon-filled HCF and chirped mirrors. We anticipate that this approach can be readily scaled up to tens of millijoules pulse energies and unprecedented average powers of hundreds of Watts.

2. Experimental results

In our study, we employed 170-fs-long pump pulses centered at 1030 nm with an energy of 1 mJ emitted by a Yb:KGW regenerative amplifier. These incident pulses are focused by means of a convex lens (f = 1000 mm) into a 6-m-long HCF with an inner diameter of 500 μm (*few-cycle* Inc.). The so-obtained input beam focal spot is about 230 μm (diameter $1/e^2$ of the intensity). Two metal tubes connected to the Ar gas line are placed at each end of the HCF. At the incident side, the pump beam is coupled into the HCF through a 1-mm-thick fused-silica window AR-coated at 1030 nm, while the output beam emerging from a 1-mm-thick uncoated fused-silica window is collimated by means of an aluminum concave mirror (f = 1000 mm). After the HCF is vacuum-pumped, Ar gas is then injected at a controlled static pressure. For all the tested pressure levels, the total transmission through the 6-m-long-HCF (including windows) is around 70%. The standard deviation of the input pulse energy (less than 0.3%) remains unchanged after the propagation through the Ar-filled HCF. The collimated output pulses are compressed by means of seven bounces on broadband chirped mirrors (-50 fs^2/each bounce) [5] and propagate through a 1-mm-thick MgF_2 window (which is used to finely adjust the overall dispersion). Finally, the pulse duration is recorded via second-harmonic FROG measurements, performed using a 10-μm-thick BBO crystal and a real-time spectrometer (Fig.1(a)).

First, we have recorded the spectra of the output pulses from the HCF as a function of the Ar pressure. To cover the whole spectral range, we have combined a visible (Ocean optics, $\lambda < 1170$ nm) and an IR (Avantes, $\lambda > 945$ nm) spectrometers. The recorded spectra have been corrected taking into account the spectrometer sensitivities, using a black body source. For an Ar pressure of 1.5 bar, significant spectral broadening is observed spanning from about 800 nm to 1200 nm (Fig.1(b)). The good symmetry of the output spectrum centered at around 1030 nm supports the idea that self-phase modulation (SPM) plays a major role in the nonlinear spectral broadening.

Following the addition of seven bounces on the chirped mirrors and the propagation through a 1-mm-thick-MgF_2 window (corresponding to a total GDD ~ 337 fs^2), the incident pulses are found to be optimally compressed from 170 fs to 5.1 fs, which corresponds to 1.5 cycles at 1030 nm (Fig.1(c)). For the considered pressure and intensity, plasma-related effects are negligible and the main process driving the spectral broadening is SPM, through the first order Kerr term n_2. Therefore, by employing the proposed strategy, we can achieve a significant spectral broadening without introducing complex spectral phase structures on the pulse envelope. This allows us to easily remove the nonlinear-induced chirp, by simply using broadband chirped mirrors to enter the single-cycle regime.

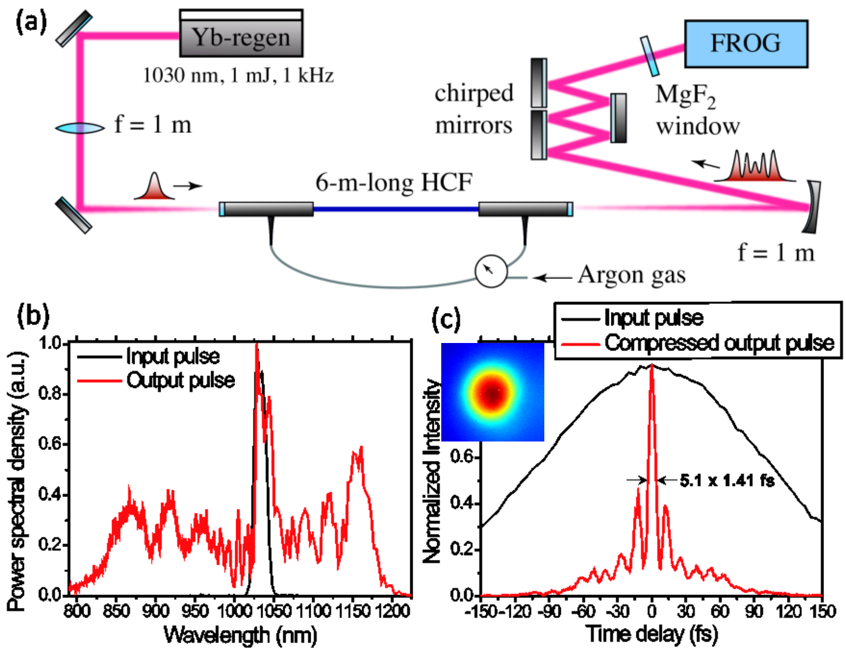

Figure 1. (a) Experimental setup. (b) Spectra of the input (black) and output (red) pulses after propagation through a 6-m-long HCF filled with 1.5 bar of Ar. (inset) the output beam mode profile. (c) Normalized autocorrelation traces of the input pulses (170 fs, black) and the compressed pulses (calculated from FROG measurement) after the optimal GDD compensation (5.1 fs, red).

3. Conclusion

We have demonstrated a straightforward and efficient way to achieve 33-fold pulse compression down to 5.1 fs in a single-pass 6-m-long Ar-filled HCF, using chirped mirrors for dispersion compensation. Remarkably, this approach should be easily scaled up to hundreds of Watts of average powers [5] and multi-millijoule pulse energies [4], thus extending the applicability of compact Yb lasers to the realms of ultrafast and strong field laser physics.

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