Two-color-field Driven Hollow-core Fiber Compressor with Robust Inline Scheme

Yudong Yang^{1,2,3,*}, Liwei Song^{2,4}, Fabian Scheiba^{1,2,3}, Giulio Maria Rossi^{1,2,3}, Roland E. Mainz^{1,2,3}, Shaobo Fang², Giovanni Cirimi², Oliver D. Mücke^{1,2}, and Franz X. Kärtner^{1,2,3}

¹The Hamburg Centre for Ultrafast Imaging CUI, University of Hamburg, 22761 Hamburg, Germany

²Center for Free-Electron Laser Science CFEL, Deutsches Elektronen-Synchrotron DESY, 22607 Hamburg, Germany

³Department of Physics, University of Hamburg, 20355 Hamburg, Germany

⁴State Key Laboratory of High Field Laser Physics, Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, 201800 Shanghai, China

*yudong.yang@cfel.de

Abstract: We present a new scheme of two-color-field driven hollow-core-fiber compression, whose ~ 1 mJ output covers 300 nm to 950 nm supporting sub-cycle pulses of ~ 2.1 fs duration. The spectral phase is characterized with two-dimensional spectral shearing interferometry. **OCIS codes:** (320.0320) Ultrafast optics; (320.5520) Pulse compression.

Energetic few-cycle laser pulses are in general the prerequisite for isolated attosecond pulse (IAP) generation. Currently, among the various methods that have been proposed to produce energetic ultrashort pulses, the noble-gas-filled hollow-core fiber (HCF) compressor is the most commonly used method [1]. In the meantime, many variations of the HCF compressor, including two-color-driving fields, pressure gradients, circularly polarized driving fields, have been developed to increase either output pulse energy or spectral bandwidth. Among these variations, the two-color-field driven HCF exploits cross-phase modulation (XPM) between the two fields to increase the output bandwidth which can support sub-cycle pulse durations. Previous demonstrations provided extremely broad bandwidth, typically with rather limited pulse energy of few μ Js [2] not suitable for IAP generation. Moreover, the two-color field was prepared with a Mach-Zehnder interferometer which introduces delay jitter between the two fields [2]. Here, we present a new configuration for a two-color-field driven HCF that provides robust, jitter-free, energetic output with ultra-broad bandwidth, which supports sub-cycle pulse duration. Meanwhile, two-dimensional spectral shearing interferometry (2DSI) [3] is used to characterize the spectral phase of the HCF output.

Fig. 1. (a) Experimental scheme of the inline configuration for generating the two-color driving field, HWP: half-waveplate, HE field: high-energy field, LE field: low-energy field, SH field: second-harmonic field; (b) HCF output spectrum under different experiment conditions: single-color driving field (purple), two-color driving field without temporal overlap (blue), and two-color driving field with different temporal overlap (red & yellow).

Our two-color-field driven HCF scheme is shown in Fig. 1(a). In contrast to the interferometric approach, we adopt an inline configuration for generating the two-color driver field. The laser pulses (800 nm, 35 fs, 2.7 mJ) from a Ti:sapphire laser system are sent onto a birefringent crystal (calcite) after propagating through a half-waveplate (HWP). The laser pulses are then split by the birefringent crystal into two delayed and orthogonally polarized replicas with pulse energies of 2.2 mJ and 0.5 mJ, respectively. The pulse energy ratio between the two replicas is adjusted by controlling the angle between the input polarization of the laser pulses and the optics axis of the birefringent crystal with a HWP. Meanwhile, the delay between the two pulse replicas is controlled with the birefringent crystal thickness. The laser beam is then focused by an $f=1.5$ m lens into a neon-filled HCF (length 1 m, inner diameter 400 μ m, gas pressure 2.8 bar). A 100- μ m thick type-I BBO for second-harmonic generation (SHG) is

placed close to the entrance window of the HCF assembly. The BBO is aligned in such a way that SHG only occurs with the pulse replica with lower pulse energy (LE). As a result, the polarization of the generated second-harmonic (SH) field is parallel to the pulse replica with higher pulse energy (HE). The pulse energy of the SH field is $\sim 100 \mu\text{J}$. To achieve temporal overlap between the SH field and fundamental HE field close to the exit of the HCF, which maximizes the cross-phase modulation, the LE field must propagate ~ 80 fs ahead of the HE field right at the exit of the birefringent crystal. This delay is introduced by a $\sim 150\text{-}\mu\text{m}$ thick calcite plate. At the exit of the HCF, the LE field travels far ahead of the synthesized two-color field and has no effect on the spectral broadening process. In future attoscience experiments, the LE field can be left unattended due to its low intensity or can be rejected with a polarizer.

When the two-color fields do not overlap in time (blue curve in Fig. 1(b)), the spectral shapes of the spectral regions neighboring the fundamental wavelength and the SH wavelength resemble the spectral shapes when each field is coupled into the HCF individually. In contrast, when the two fields overlap in time, cross-phase modulation between the two fields modifies the spectral shape into a broad supercontinuum. The ultra-broad bandwidth two-color-field driven HCF output (~ 1 mJ) is shown in Fig. 1(b) as red curve, which covers the spectral range from 300 nm to 950 nm. The spectrum corresponds to a sub-cycle transform-limited pulse duration of ~ 2.1 fs. Moreover, by fine tuning the amount of temporal overlap, one can control the spectral shape, such as change from the red to orange curve in Fig. 1(b), which is a highly attractive feature for optical waveform control.

Fig. 2. (a) Experimentally measured 2DSI spectrogram of the spectral phase of the HCF output spectrum, the spectrogram is converted back to the spectral range of the fundamental spectrum, and the retrieved group delay (GD) is shown as black curve; (b) same as (a), but after recompression by means of several reflections on chirped mirrors; (c) spectral intensity (blue) and spectral phase (red) of the HCF output. The spectral phase right after the HCF is shown as red solid line, while the spectral phase of the pulse after chirped mirrors is shown as red dashed line.

Measuring the spectral phase over such an ultra-broad bandwidth is a challenging task in itself. Here we employ 2DSI to measure the spectral phase. The measured 2DSI spectrogram is shown in Fig. 2(a), from which the group delay (GD) over the whole spectrum is extracted. It is found that the chirp is well-behaved and the spectral phase is smooth without any discontinuity (Fig. 2(c), red curve), which indicates that the pulses are compressible. To demonstrate that the dispersion can be compensated to an extent with currently available chirped mirrors over a reduced wavelength range, the HCF output is guided through home-designed chirped mirrors with constant group-delay dispersion (GDD) of -240 fs^2 from 500 nm to 1000 nm. The measured 2DSI spectrogram of the dispersion-compensated spectrum is shown in Fig. 2(b), which clearly indicates that the group delay is mostly compensated within the negative GDD range of the chirped mirrors. Fig. 2(c) shows that the spectral phase of the dispersion-compensated spectrum has changed its sign after reflections on chirped mirrors. In conclusion, we present a robust inline configuration for implementing two-color-field driven HCF, which delivers ultra-broadband, energetic and stable output. Provided that the dispersion can be properly compensated, e.g., by means of custom-designed chirped mirrors, the available energetic sub-cycle pulses will become a highly promising tool for attoscience applications.

References

- [1] M. Nisoli, S. De Silvestri, and O. Svelto "Generation of high energy 10 fs pulses by a new pulse compression technique," *Appl. Phys. Lett.* **68**, 2793–2795 (1996).
- [2] E. Matsubara, K. Yamane, T. Sekikawa, and M. Yamashita, "Generation of 2.6 fs optical pulses using induced-phase modulation in a gas-filled hollow fiber," *J. Opt. Soc. Amer. B* **24**, 985–989 (2007).
- [3] J. R. Birge, R. Ell, and F. X. Kärtner, "Two-dimensional spectral shearing interferometry for few-cycle pulse characterization," *Opt. Lett.* **31**, 2063–2065 (2006).