Novel soliton self-compression spectral dynamics in air-filled Kagome HCPCF

Martin Maurel, Foued Amrani, Ihar Babushkin, Benoit Debord, Frédéric Gérôme, Fetah Benabid

To cite this version:

Martin Maurel, Foued Amrani, Ihar Babushkin, Benoit Debord, Frédéric Gérôme, et al.. Novel soliton self-compression spectral dynamics in air-filled Kagome HCPCF. European Optical Society Annual meeting (EOSAM) 2021, Sep 2021, Rome, Italy. pp.481. hal-03355003

HAL Id: hal-03355003
https://hal.archives-ouvertes.fr/hal-03355003

Submitted on 27 Sep 2021

Novel soliton self-compression spectral dynamics in air-filled Kagome HCPCF

Martin Maurel[1,2] *, Foued Amrani*[1,2]*, Ihar Babushkin*[3,4]*, Benoit Debord*[1,2] *, Frédéric Gérôme*[1,2] *and Fetah Benabid*[1,2]*.*

[1]GPPMM group, Xlim laboratory, CNRS- Université de Limoges, France
[2]GLOphotonics, 123 avenue Albert Thomas Limoges, France
[3]Institute of Quantum Optics, Leibnitz Hannover University, Hannover, Germany
[4]Cluster of Excellence PhoenixD Welfengarten 1, 30167 Hannover, Germany

Abstract. We report on a nonlinear compression down to 20 fs in air-filled HCPCF. Novel spectral-temporal dynamic is observed and analysed. The results represent a promising pathway for strong and stable compression of current commercial ultra-short-pulse lasers

Inhibited-Coupling hollow-core photonic crystal fibers (IC-HCPCF) proved to be an excellent platform for pulse-compressing high-energy ultrashort optical pulses (HE-USP) [1-3]. As a matter of fact, IC-HCPCF created a new paradigm in the propagation dynamics of HE-USP, thanks to its unique combination in withstanding high laser energy, engineering its dispersion and controlling the optical nonlinearities via the large controlling space-parameters via the choice of gas and its pressure [4]. Notably, in addition to the common nonlinear optical effects such as self-phase-modulation (SPM), four-wave mixing (FWM), stimulated Raman scattering (SRS), gas-filled IC-HCPCF stands out with specific plasma-induced dynamics such as that of “floating” solitons [2]. In [2], a theoretical model treated the case of single mode propagation in an inert gas, and showed that self-compression of USP with ionizing intensities is initiated by the onset of plasma, and is followed by a strong soliton-fission manifested as a ‘shower’ of hundreds of solitons. Conversely, some gas media can be Raman active, such as atmospheric air, which creates a situation where both plasma blueshift (PBS) and soliton self-frequency redshift (SSFRS) could take place, thus opening an exciting means of controlling the soliton spectral dynamics. Whilst the interplay between PBS and SSFRS has been the subject of several theoretical work, little experimental work has been done so far on the subject [5].

Here, we report on experimental and theoretical results related to the propagation dynamics of an HE-USP in a few meter long air-filled IC-HCPCF. In particular, we show the role of plasma, Raman scattering and IC-HCPCF higher order modes (HOM) in the self-compression of optical pulses with duration of ~600 fs and energy in the range 100-300 µJ down to ~20 fs with little energy loss and in a stable manner. Furthermore, we show, for the first time to our knowledge, experimentally and theoretically, soliton spectral oscillation between blueshift and redshift as the input pulse energy is increased.

Fig. 1 summarizes the experimental results. The experiment consists of propagating a ~600 fs duration Yb-based laser with energy range of 100-300 µJ and central wavelength at 1030 nm in a 4 meter long Kagome IC-HCPCF exposed to atmospheric pressure. The fiber has an inner diameter of 60 µm. At the laser wavelength, the transmission loss is 20 dB/km, the group velocity dispersion (GVD) is β_2=-480 fs^2/m, the third order dispersion (TOD) is β_3=1330 fs^3/m, and the zero GVD wavelength is 803 nm. Fig. 1a shows the frequency-resolved optical gating (FROG) evolution when the energy is increased from 115 µJ to 253 µJ. The FROG traces (Fig.1a) show a sequence of compression and temporal broadening within the range of 20-100 fs, along with spectral blue and redshift. The results show striking difference between the input pulse and the output compressed pulse (Fig. 1b). Fig. 1c shows the pulse central wavelength spectral shift with increasing input energy. In 115-150 µJ range, the pulse goes through a continuous compression and red shift from from 1037 nm to 1065 nm respectively. For 150-180 µJ, the double process of compression and redshift stops before a sudden blue shift back to 1035 nm for input energy between 180 µJ and 190 µJ. The blueshift is accomplished with a slight temporal broadening. For the range of 190-250 µJ, a second sequence of compression and redshift takes place. We attribute this “spectral bouncing” to the interplay of plasma, which induces PBS and intrapulse Raman scattering which is behind SSFRS. Noteworthy is the high stability of the compressed pulse (Fig. 1d) despite the theoretically predicted sensitivity due to soliton fission. Fig. 2 summarizes the numerical results of the spectral and temporal dynamic and the electron fractional density evolution for an input energy of 200 µJ. Here the pulse propagation in the IC-HCPCF is numerically solved using

---

[*] Corresponding author: f.benabid@xlim.fr

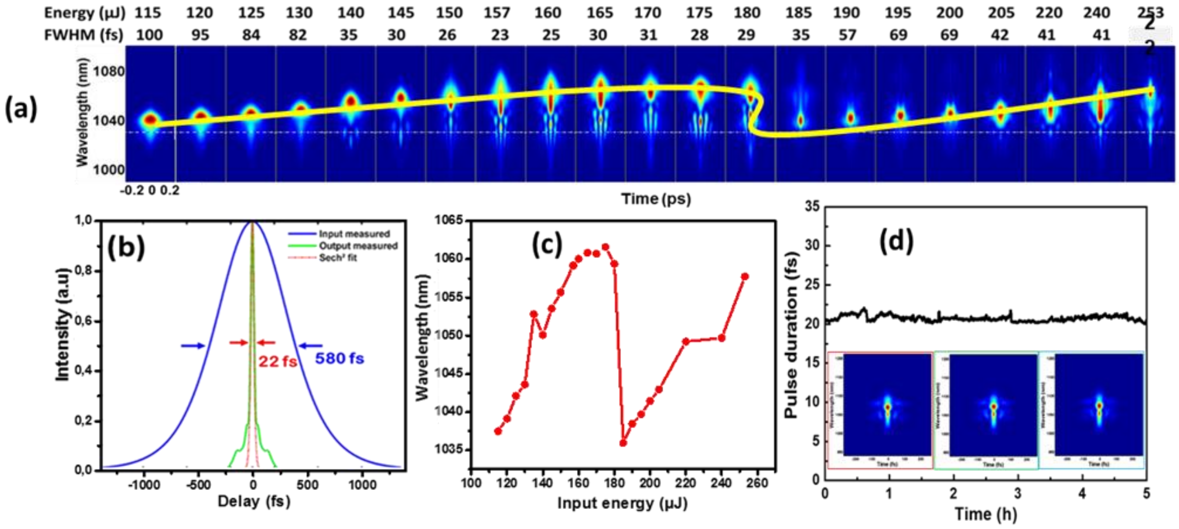

Fig. 1. (a) FROG evolution with input pulse energy. (b) Typical auto-correlation trace of the input pulse (blue) curve and the output pulse (green curve). The red doted curve is a sech2 fit. (c) Evolution with input energy of central wavelength. (d) Time stability of the output pulse FWHM.

the full multi-modal nonlinear Schrodinger equation (MMNLSE) including the terms associated to plasma effect, Kerr and Raman in air. Each fiber mode is represented by its own dispersion (gas contribution included) and transverse profile.

In the present case, we limit to the first 4 LP_{0m} modes where the fiber coupling at the input is done in way where 95% of the power is in LP01, 3% in LP02 and 1% in LP03 and LP04. The figure shows, LP_{01} spectro-temporal distribution and the modes electron density evolution. The stronger spectral broadening happen associated with a sudden and strong solitonic compression. Around 1 m, the pulse (which is higher order soliton) starts to shorten and its spectrum is broadening. This shortening process results on the separation of a fundamental soliton from the main pulse. At 2,2 m the intensity is high, ionization is high and higher order modes are effectively produced. Also the most of spectrum broadening take place at this stage and the spectral bouncing occurs. The electron density evolution of different modes start to increase when the high compression of the initial starts to the have a maximum at the spectral bouncing point. The sudden compression is followed by an oscillatory behavior in the plasma density, which associate to the report concept of “floating soliton”.

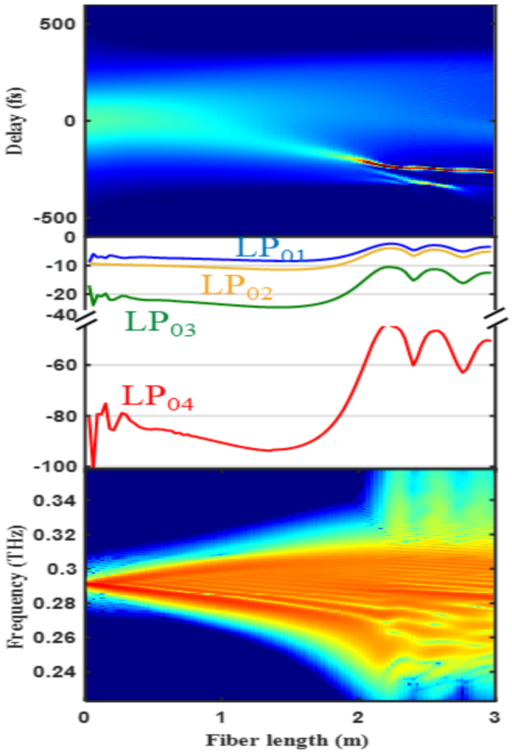

Fig. 2. (a) temporal evolution, (b) electron fractional density evolution and (c) spectral evolution.

The result clearly indicate that the modal content is a driving factor in our observed experimental results and with a qualitative agreement with the experiment. Simulation work with better-matched parameters such as the modal loss and dispersion or ionisation rate with experiment, and including other types of HOM is ongoing.

In conclusion, strong and stable self-compression with ionizing intensities and new spectral-shift dynamics of a 580 fs pulse propagation in air is experimentally observed. The effect are qualitatively reproduced numerically using MMNLSE. Further work is ongoing to investigate the remaining discrepancies between experiment and the numerical model.

References

1. T. Balciunas, et al., Nature Communications, **6**, N6117, (2015).
2. M.Saleh et al., J. Opt. **18**. pp 013002 (2016).
3. B.Debord, et al., Photonics Research 7(10), 1134 1141 (2019).
4. B. Debord et al., Opt. Express, 22(9), 10735-10746 (2014).
5. M. Maurel, et al., CLEO/Europe-EQEC), Munich, 2019, pp.