Soliton self-compression in air filled Kagome HCPCF

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Hollow-core photonic crystal fibre (HCPCF) proved to be a powerful platform for optical pulse compression. Several results, reported in the last few years, show both exceptional compression performances over a large energy dynamic range and varied experimental conditions [1][2][3], and new physical dynamics [4]. Among the reported performances, we list those achieved with Inhibited-Coupling guiding HCPCF (IC-HCPCF), and where soliton self-compression down to the single or a few cycle regime were achieved with a $\sim 1.8 \mu\text{m}$ wavelength and 80 fs duration input-pulse [1], and with a 790 nm wavelength and 24 fs duration input-pulse [2]. Conversely, the low values and spectral profile of the IC-HCPCF dispersion, combined with its fine control through a judicious choice of a filling gas, enabled the observation of several nonlinear optical regimes as varied as modulation instability, self-phase modulation, supercontinuum generation, or plasma-induced soliton blue-shift and fission. Remarkably, in the latter regime, experimental and theoretical results show that soliton-plasma interaction and its high sensitivity to the input laser and IC-HCPCF parameters are overarching several novel solitonic phenomena[4]–[6] such as strong soliton self-compression, blue and red frequency-shift and fission. Here, we report on experimental observations of soliton self-compression and temporal-spectral propagation dynamics of 100 microJoule-scale ultra-short pulse (USP). The frequency-resolved optical gating (FROG) results show the compression of 580 fs to a highly stable 22 fs pulse in a single stage, and the observation of an original sequence between soliton red and blue frequency-shift for input pulse energy range of 100-250 μJ .

The experimental set-up consists of a few meter long Kagome IC-HCPCF exposed to atmospheric air and excited with USP laser. The latter is a 580 fs duration Yb-based laser with a maximum energy of 1 mJ, a central wavelength of 1030 nm and the repetition rate of 1 kHz. The fibre has an inner core diameter of 57 μm , a loss of 30 dB/km and group velocity dispersion (GVD) of $\beta_2 = -300 \text{ fs}^2/\text{m}$ at the laser wavelength. Fig 1(a) shows the FROG evolution of the output from a 4 m long fibre with the input energy, from 115 μJ to 255 μJ . Within this range, the results show a 100 fs wide soliton self-compressed and red-shifted pulse at 115 μJ to further frequency red-shift with increasing energy, to reach a 22 fs pulse at 158 μJ (*i.e.* Intensity $\sim 10 \times 10^{14} \text{ W}/\text{cm}^2$, and comparable with the air ionisation). For the energy range 157-180 μJ , the FROG shows a more structured spectrogram corresponding to soliton fission, and moderate temporal broadening. At 185-190 μJ range, a sudden strong blue-shift and temporal broadening takes place, after which the pulse triggers another red-shift and then compression sequence to reach a duration of 23 fs at 253 μJ . We associate this novel dynamics to the interplay between an onset of photo-ionisation, which induces plasma and soliton blue-shift, with soliton formation and Raman red-shift [4]. Despite the high sensitivity of this phenomenon, the compressed pulse is highly stable. Figs. 1(b) and 1(c) summarises this observation at an input energy of 158 μJ . The autocorrelation traces (Fig.1(b)) show a compressed and close to sech²-shaped (red dashed curve) pulse of 22 fs (Green curve), which 26 narrower than the input pulse (blue curve). The pulse-width from 2 m long fibre was monitored over 5 hours (Fig. 1(c)), and was found to be 21 fs with standard deviation of only of 0.3 fs.

Fig. 1 (a) Spectral and temporal evolution of the output pulse with energy, (b) Autocorrelation traces of the compressed and input pulses at 158 μJ input energy, (c) Pulse-width evolution with time over 5 hours of continuous running.

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