Optical attosecond pulses and bright VUV generation from soliton dynamics in hollow capillaries

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Abstract: Soliton dynamics in large-core gas-filled hollow capillary fibres can create high-energy sub-femtosecond and few-femtosecond pulses tuneable across the vacuum ultraviolet to infrared. Our work provides a new platform technology for ultrafast science.

The creation of optical pulses with ever shorter durations, ever higher energies, over ever wider spectral ranges is a central topic in nonlinear optics, driven by both a fundamental curiosity about the physical limits and the increasing demands of cutting-edge science such as ultrafast spectroscopy. In conventional solid-core optical fibres, the use of soliton dynamics to achieve pulse compression and frequency conversion is well established; perhaps most clearly illustrated by the creation of white-light supercontinuum spectra. However, solid-core fibers cannot be used to access the very deep and vacuum ultraviolet spectral regions—simply due to absorption and dispersion from the electronic resonances of all glass materials. The use of ultrafast soliton dynamics in gas-filled hollow-core microstructured fibres [1, 2] has been highly successful in overcoming this constraint [3, 4], but current schemes suffer from two limitations. Firstly, the existing microstructured fiber designs have moderate core sizes (tens of µm), limiting the maximum energy which can be coupled before the high intensity breaks down the filling gas. Secondly, the microstructure introduces optical resonances, which affect both the transmission and the dispersion. While both effects can be tolerated to a large extent, they become critically important for two of the most promising applications—in the ultraviolet, resonant coupling of light into the glass reduces the waveguide lifetime; while compression to multi-octave-spanning sub-cycle pulses is disturbed by the fibre resonances. Recently we have proposed and demonstrated the use of simple gas-filled hollow capillary fibres (HCF) for ultrafast soliton dynamics [5]. The large core sizes available allow scaling the pulse energies up to the multi-mJ level, and the peak power

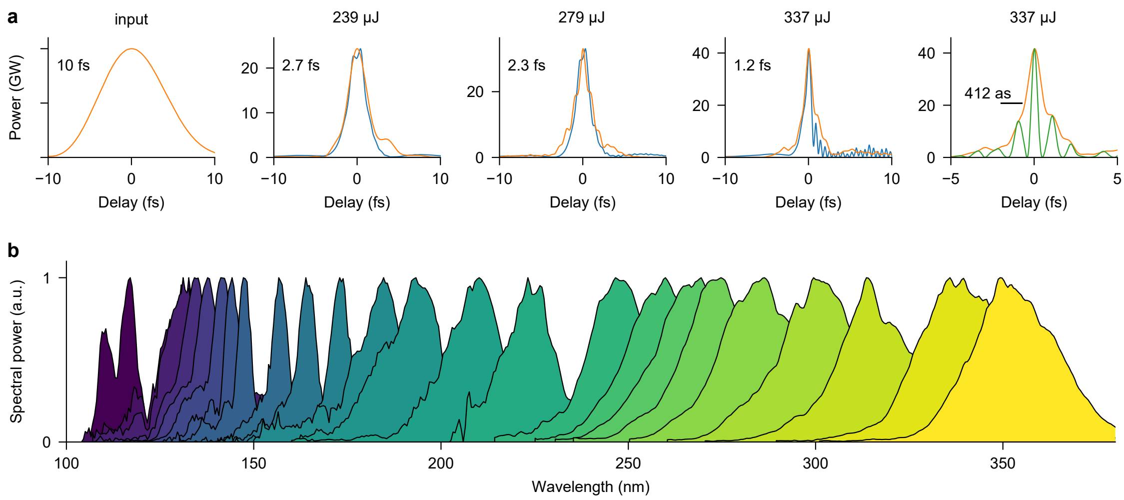

Fig. 1. (a) Self-compression of 10 fs, 800 nm pulses in a 3 m long, 250 µm diameter HCF filled with 0.4 bar helium. The orange curves are measurements and the blue curves are numerical simulations. (b) Experimentally measured tuneable few-fs pulses across the vacuum and deep ultraviolet generated by RDW emission under the same conditions as (a) but for different gas pressures and energies for each spectral peak shown. The output energies range from ∼ 1 µJ around 120 nm to 15 µJ around 200 nm. After [5].

can potentially exceed 1 TW. Furthermore, the lack of resonances provides unperturbed guidance of the whole spectrum.

Fig. 1 shows examples of our results. Fig. 1(a) shows measurements of soliton self-compression of a 10 fs pump pulse down to a duration of just 1.2 fs. The field of such a pulse consists of a single optical attosecond pulse of 412 as duration and 40 GW peak power. Such pulses can be used, for example, for sub-femtosecond resolution measurements of bound-electron dynamics [6], where one requires attosecond pulses at much lower photon energy than achievable through high-harmonic generation. Fig. 1(b) shows tuneable high-energy pulses generated through resonant dispersive-wave (RDW) emission. Such pulses are ultrafast—numerical simulations suggest 1 fs to 3 fs, and measurements in the DUV in PCF have shown ~ 3 fs [7]—very bright (the pulses shown here contain ~ 1 μJ around 120 nm up to 15 μJ around 200 nm), and can be tuned continuously over a wide spectral range. Such a light source is of great importance to, for example, advanced ultrafast pump-probe spectroscopy.

Our initial demonstration was in a long (3 m) HCF. We have subsequently shown that, by using shorter pump pulses and smaller core diameters, it is possible to obtain similar results in much shorter lengths (15 cm) [8]. Furthermore, we have demonstrated that moving from a driving wavelength of 800 nm to 1800 nm allows for the creation of the shortest infrared optical pulses to date—2 fs in duration—an ideal driver for strong-field physics [9]. The longer driving wavelength also extends the tuning range of the RDW emission to the near infrared.

Currently, we are investigating the full breadth of dynamics observable as the dispersion landscape is tuned, as pressure gradients are employed inside the fiber, or when we make use of molecular gases. Furthermore we are pursuing multiple application experiments to demonstrate the utility of this new light source.

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