High-Energy VUV Generation in Gas-Filled Hollow Capillary Fibers

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John C. Travers*, **Teodora F. Grigorova and Federico Belli**

School of Engineering and Physical Sciences, Heriot-Watt University, Edinburgh, EH14 4AS, United Kingdom

**j.travers@hw.ac.uk*

Abstract: We show that soliton dynamics scale to millijoule energies in simple hollow capillary fibers. We numerically model sub-femtosecond pulse self-compression, and experimentally demonstrate high-brightness multiple-μJ-scale ultraviolet (115-330 nm) pulse generation.

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In this paper we demonstrate that, by carefully combining both nonlinear and dispersive effects, soliton dynamics can be harnessed in large-core (100 μm to 1 mm diameter) hollow capillary fiber (HCF). Most of the ultrafast soliton effects demonstrated in recent years in gas-filled hollow-core microstructured fibers (such as anti-resonant guiding, kagome-style photonic crystal fiber) [2, 3], can be significantly scaled in energy by using HCF, by at least two orders of magnitude. Here we numerically and experimentally explore coherent soliton self-compression, leading to sub-femtosecond pulse durations, multi-octave supercontinuum generation and subsequent fission dynamics. In particular, we experimentally demonstrate resonant dispersive-wave emission in the deep (DUV) and vacuum (VUV) ultraviolet (115-330 nm), with measured pulse energies in the VUV exceeding 20 μJ.

For resonant dispersive-wave emission to occur at extreme frequencies, the pump pulse must undergo soliton-effect self-compression until it reaches a sub-femtosecond pulse duration and a multi-octave spanning spectral width [2, 3]. At this point a resonant transfer of energy can occur to particular phase-matched frequencies. This compression and emission point approximately occurs at the soliton fission length $L_{\mathrm{fiss}} = L_d/N$, where L_d is the dispersion length and N the soliton order [4]. For HCF it can be shown that $L_{\mathrm{fiss}} \propto \tau_0^2 a^2/N$, where τ_0 is the pump pulse duration and a is the HCF core radius. In microstructured fibres, the low guidance loss for small a allows one to achieve soliton self-compression and fission in short length scales. In conventional HCF, the large a means that either very large length scales are required, or short pump pulses. Following the pioneering work of Nagy et al. [5], we make use of 3 m long stretched capillary fibers, to extend the length scale over which soliton dynamics can occur, and pump with 10 fs pulses from a conventional HCF compressor system to reduce L_{fiss}.

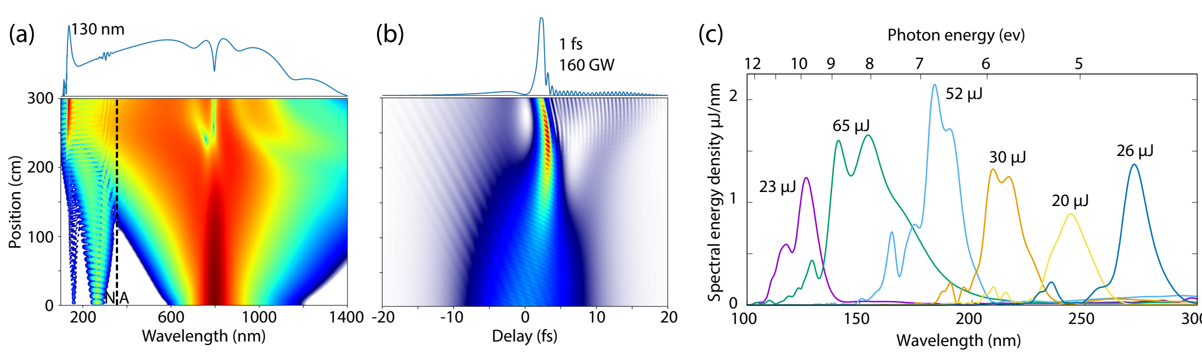

Fig. 1. Numerically modelled spectral (a) and temporal (b) evolution of a 10 fs, 800 nm, 0.5 mJ pump pulse in a 250 μm inner diameter HCF filled with 0.3 bar He. N, A indicate normal and anomalous dispersion regions. (c) Optimized VUV dispersive-wave emission peaks, for different He gas pressures.

Fig. 1(a,b) shows one example simulation using our rigorous, fully vectorial and spatially resolved, unidirectional pulse propagation code, which includes ionization, plasma effects, self-focusing, and polarization effects. A wide range of parameters have been modelled and will be presented, but this example is illustrative, and coincides with the experiments described below. In this case we show the self compression of a 10 fs, 800 nm, 0.5 mJ pump pulse to 1 fs, in a 250 μm inner diameter HCF filled with 0.3 bar He. For these parameters, the zero dispersion point is at 355 nm, and soliton order is $N = 2.5$. Scaling these dynamics to the multi-mJ, terrawatt-power regime is realistic in larger core HCF, and will be presented. At the self-compression point, generation of a dispersive-wave at 130 nm occurs. The energy transfer to the VUV can be extremely efficient, and we predict VUV pulse energies exceeding 50 μJ in sub-femtosecond pulses, as shown in Fig. 1(c).

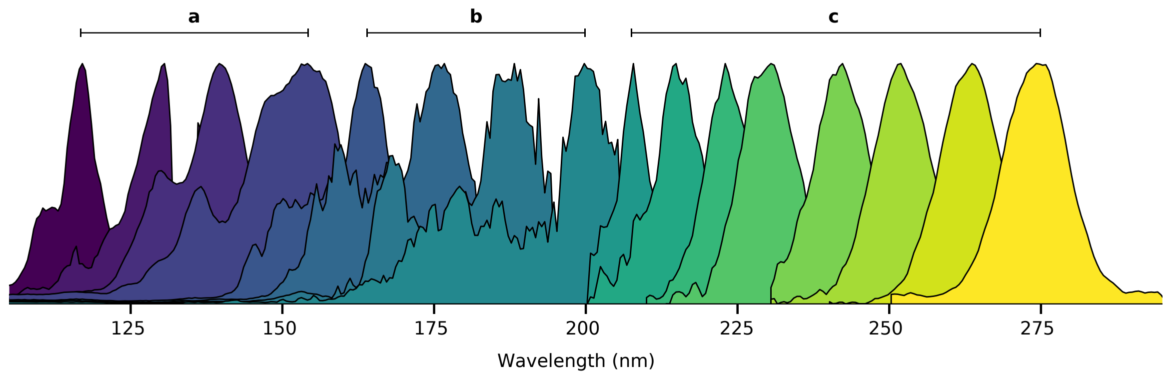

Fig. 2. Normalized experimental spectra obtained with ∼ 10 fs pump pulses in a 3 m long, 250 μm inner-diameter capillary filled with He and Ne. (a) A pump energy of ∼ 450 μJ in He gas, from left to right: 230 mbar, 350 mbar, 404 mbar, 550 mbar; (b) a pump energy of ∼ 330 μJ in Ne gas, from left to right: 400 mbar, 500 mbar, 600 mbar, 700 mbar; (c) Ne gas, from left to right: ∼ 275 μJ, 500 mbar; ∼ 275 μJ, 550 mbar; ∼ 225 μJ, 610 mbar; ∼ 205 μJ, 698 mbar; ∼ 265 μJ, 787 mbar; ∼ 180 μJ, 898 mbar; ∼ 185 μJ, 1016 mbar; ∼ 170 μJ, 1157 mbar.

In our experiments, bandwidth limited pulses at around 800 nm, with a duration tunable from 6 fs to 30 fs, are produced in a conventional hollow fiber compressor system based on a stretched, 1.6 m long, 450 μm inner diameter HCF. The compressed pulse energy can be tuned up to 1 mJ. For the current results, we set the pulse duration to 10 fs, and coupled them into a 3 m long stretched hollow capillary fiber, with an inner diameter of 250 μm. By tuning the gas pressure, gas species (He and Ne) and pump energy, we can tune the emitted RDW wavelength from 115 nm to beyond 275 nm, as shown in Fig. 2.

The VUV and DUV RDW energies can be obtained from the absolute calibration of our VUV spectrometer. The first peak in Fig. 2a, at 115 nm, contains 350 nJ. As we tune to longer wavelengths the energy substantially increases, to around 1 μJ in the 120 nm to 130 nm region, more than 3 μJ around 140 nm, and over 20 J from 150 nm and longer wavelengths.

When fully scaled, this table-top light source will have a brightness within a few orders of magnitude of a synchrotron in the VUV, with dramatically reduced cost and complexity, but also with a temporal resolution that exceeds free-electron laser systems. The new regime of soliton dynamics discussed here promises to be the basis of a new class of light-sources for ultrafast science.

References

1. M. Nisoli, S. Stagira, S. De Silvestri, O. Svelto, S. Sartania, Z. Cheng, G. Tempea, C. Spielmann, and F. Krausz, "Toward a terawatt-scale sub-10-fs laser technology," IEEE Journal of Selected Topics in Quantum Electronics **4**, 414–420 (1998).
2. J. C. Travers, W. Chang, J. Nold, N. Y. Joly, and P. St.J. Russell, "Ultrafast nonlinear optics in gas-filled hollow-core photonic crystal fibers [Invited]," Journal of the Optical Society of America B **28**, A11–A26 (2011).
3. C. Markos, J. C. Travers, A. Abdolvand, B. J. Eggleton, and O. Bang, "Hybrid photonic-crystal fiber," Rev. Mod. Phys. **89**, 045,003 (2017).
4. J. M. Dudley, G. Genty, and S. Coen, "Supercontinuum generation in photonic crystal fiber," Reviews of Modern Physics **78**, 1135 (2006).
5. T. Nagy, M. Forster, and P. Simon, "Flexible hollow fiber for pulse compressors," Applied Optics **47**, 3264–3268 (2008).