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Experimental Demonstration of High-Energy Deep Ultraviolet Pulse Generation Through Soliton Dynamics in Gas-Filled Hollow Capillary Fibers

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Abstract: Using soliton dynamics in 250 μm diameter Ne-filled hollow capillaries, we generate tunable, > 5 μJ, ultrafast pulses in the deep ultraviolet (200-330 nm). Further energy scaling and extension to the vacuum ultraviolet is predicted.

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The use of soliton-driven resonant dispersive-wave emission to generate tunable, ultrafast, deep (DUV) and vacuum (VUV) ultraviolet pulses in gas-filled hollow-core microstructured fibers, such as anti-resonant guiding, kagome-style, photonic crystal fibers [1–3], has become well established. Typically the emitted energy is ~ 100 nJ in the DUV, and less in the VUV. In this paper we demonstrate significant scaling of these energies by accessing soliton dynamics in simple, large-core, hollow capillary fibers (HCF). The full implications of accessing high energy optical solitons in HCF, including details of the extreme self-compression dynamics that are possible, are discussed in a separate submission [4]; here we concentrate on high energy ultraviolet generation.

To generate the DUV and VUV radiation we use the process of resonant dispersive-wave emission from optical solitons [1–3]. For this to occur at extreme frequencies, the pump pulse must undergo soliton-effect self-compression until it reaches a sub-femtosecond pulse duration and multi-octave spanning spectral width. 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 $L_{\text{fiss}} = L_d/N$, where L_d is the dispersion length and N the soliton order [5]. For HCF it can be shown that $L_{\text{fiss}} \propto \tau_0^2 a^2/N$, where τ_0 is the pump pulse duration and a is the HCF core size [4]. 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. [6], we make use of 3 m long stretched capillary fibers, to extend the length scale over which soliton dynamics can occur, and pump with 8 fs pulses from a conventional HCF compressor system to reduce L_{fiss}.

At the soliton fission point, the generation of dispersive-waves occurs at the resonant frequencies, obtained by solving the phase-matching condition $\Delta\beta(\omega) = \beta(\omega) - \beta_{\text{NL}}(\omega) = 0$, where $\beta_{\text{NL}}(\omega)$ is the propagation constant at frequency ω including any terms causing a nonlinear phase-shift, and $\beta(\omega)$ is the usual linear propagation constant. When the pump pulse is a soliton in the anomalous dispersion region, a rough approximation to the emitted frequency is given by [3] $\omega = 3\omega_{\text{zd}} - 2\omega_{\text{p}}$, where ω_{p} is the pump frequency, and ω_{zd} is the zero dispersion frequency. In gas-filled HCF, ω_{zd} is tunable simply by tuning the gas pressure and hence so is the frequency of the emitted dispersive-wave.

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 8 fs, and coupled them into a 3 m long stretched hollow capillary fiber, with an inner diameter of 250 μm. Clear spectral signatures of self-compression were observed [4] (Fig. 1a), leading to the emission of a bright dispersive-wave peak in the DUV. As is characteristic of dispersive-wave emission, this peak was tunable with both gas pressure and pump power (tuning the linear and nonlinear contributions to the phase-matching condition respectively). Fig. 1b shows the experimentally measured pressure-tunable dispersive-wave emission, for gas pressures ranging from 500 mbar (short-wavelength peak) to 1300 mbar (long-wavelength peak). For each pressure, the pump energy was chosen for optimal dispersive-wave emission, in the range from 150 μJ to 300 μJ. The generated DUV energies from these preliminary results were in the range of 5 μJ to 8 μJ, but we expect, on the basis of rigorous full-field unidirectional pulse propagation simulations [4], to be able to scale these energies to the range of 50 to 100 μJ [4], in this core size, and to significantly higher energies in larger core HCF. In addition, by switching to He gas, and measuring with a

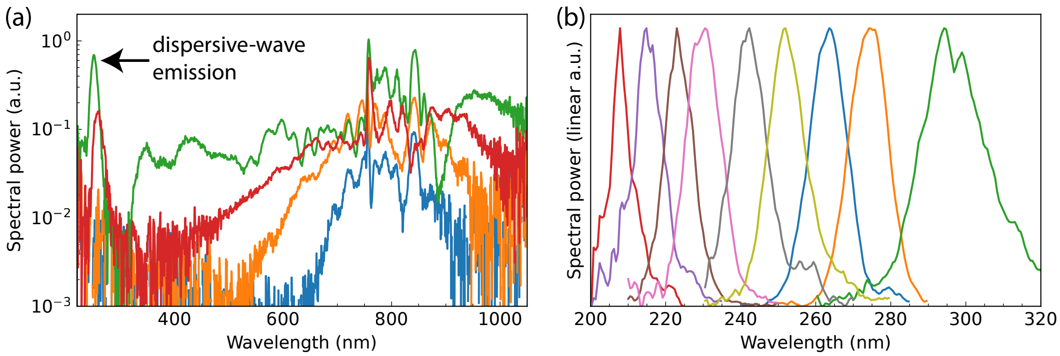

Fig. 1. Experimental results obtained with ~ 8 fs pump pulses in a 3 m long, 250 μm inner-diameter, Ne-filled capillary. (a) Evolution of supercontinuum spectrum with increasing pump energy (25 μJ to 300 μJ). (b) Experimental tuning of DUV dispersive-wave emission. Each peak is for a different gas pressure, which ranges from 500 mbar (short-wavelength peak) to 1300 mbar (long-wavelength peak). For each pressure, the pump energy was chosen for optimal dispersive-wave emission, in the range from 150 μJ to 300 μJ.

vacuum ultraviolet spectrometer (under construction) we expect to generate high-brightness tunable emission in the VUV, down to at least 110 nm, in line with previous work in microstructured fibres [3], but again, at much higher emitted energies. Fig. 2 shows example numerical simulation results.

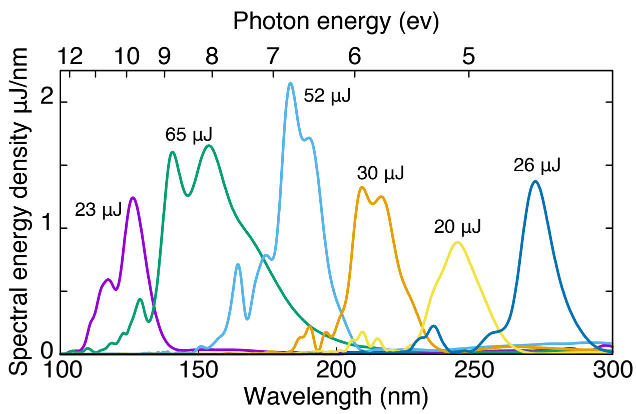

Fig. 2. Numerical simulation results for pressure-tuned dispersive-wave emission in the VUV, for parameters similar to the experiments reported in this paper, but for lower pressures, and He rather than Ne gas.

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