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Scaling Soliton Dynamics in Hollow Fibers

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: Soliton dynamics in the visible and near-infrared can be scaled to millijoule energy levels and terrawatt peak powers in simple hollow capillary fibers. We describe sub-femtosecond pulse self-compression and very high-brightness vacuum ultraviolet generation.

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1. Introduction and brief theory

The use of large-core (100 μm to 1 mm diameter) hollow capillary fiber (HCF) for self-phase modulation (SPM) based pulse compression is widely established as the primary route to create the high-energy few-cycle pulse sources required for high-field experiments [1]. In such experiments the HCF is used purely for nonlinear phase modulation, and the weak linear dispersion is largely neglected. In this paper we demonstrate that, by carefully combining both nonlinear and dispersive effects, soliton dynamics can be harnessed in 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. These include soliton-effect self-compression to sub-femtosecond pulse durations, tunable deep ultraviolet and vacuum ultraviolet pulse generation, plasma-soliton effects and ultrafast Raman-soliton scattering [2, 3].

We concentrate here on coherent soliton self-compression, leading to sub-femtosecond pulse durations, multi-octave supercontinuum generation and subsequent fission dynamics. In HCF the group velocity dispersion, and the location of the zero dispersion wavelength λ_{zd}, is tunable simply by changing the gas pressure, and so it is straightforward to set the pressure such that $\lambda_{zd} < \lambda_0$, the pump wavelength. This ensures that the pump pulse is in the anomalous (negative) dispersion spectral region, as required for bright soliton dynamics in media with positive nonlinear refractive index. To obtain self-compression the pump pulse energy is set such that the soliton order $N = (L_d/L_{nl})^{1/2}$ is in the range $1 < N \leq 15$ (larger N lead to incoherent modulational instability dynamics, which are interesting in HCF, but beyond our current scope), where L_d is the dispersion length, and L_{nl} is the nonlinear length. Soliton self-compression typically occurs over a length scale $L_{fiss} = L_d/N$ [4].

In HCF, the dispersion and other guidance properties are analytically described, and it is possible to show that, for a fixed combination of λ_{zd} and λ_0, the soliton fission length scales as $L_{fiss} \propto \tau_0^2 a^2/N$, where τ_0 is the pump pulse duration and a is the HCF core size. In hollow-core microstructured fibers, a is usually kept quite small (around 30 μm), and $L_{fiss} \sim 0.1$ m. Our goal here is to significantly increase a, to enable the use of larger pulse energies, and so inevitably L_{fiss} will also increase. To successfully obtain self-compression we must ensure that $L_{fiss} < L_{loss}$ the $1/e^2$ power loss length, which scales as $L_{loss} \propto a^3$. There are two techniques to deal with this. Firstly, we can use the stretched HCF technique developed by Nagy et al. [5] to eliminate the large HCF bend loss while increasing the length. In this way large-core HCF with lengths of 5 m have been used, and even longer lengths are possible (given sufficient laboratory space). Secondly, we can use a conventional HCF compressor as a first stage, to produce shorter pump pulses, down to ~ 4 fs, which significantly reduces L_{fiss}. A possible third technique of increasing N is less useful, as the maximum allowable N is limited due to peak power and intensity limits arising from self-focusing effects and ionization. Our analysis, which will be presented, has found that the maximum permissible N is actually independent of HCF core size a. In addition, we wish to keep $N < 15$ and preferably significantly lower, as the quality of the soliton self-compression degrades for high N. Fig. 1(a,b) show the relative L_{fiss} and L_{loss} as a function of HCF core size for both 25 fs and 8 fs pump pulses. In both cases soliton self-compression can be achieved within 5 m lengths, but for 8 fs pump pulses, even more practical lengths of less than 1 m are usable.

2. Numerical simulations

Fig. 1(c,d) show some example results of rigorous, full vector, spatially resolved, unidirectional pulse propagation equation simulations; which include ionization, plasma effects, self-focusing, and polarization effects. A wide range

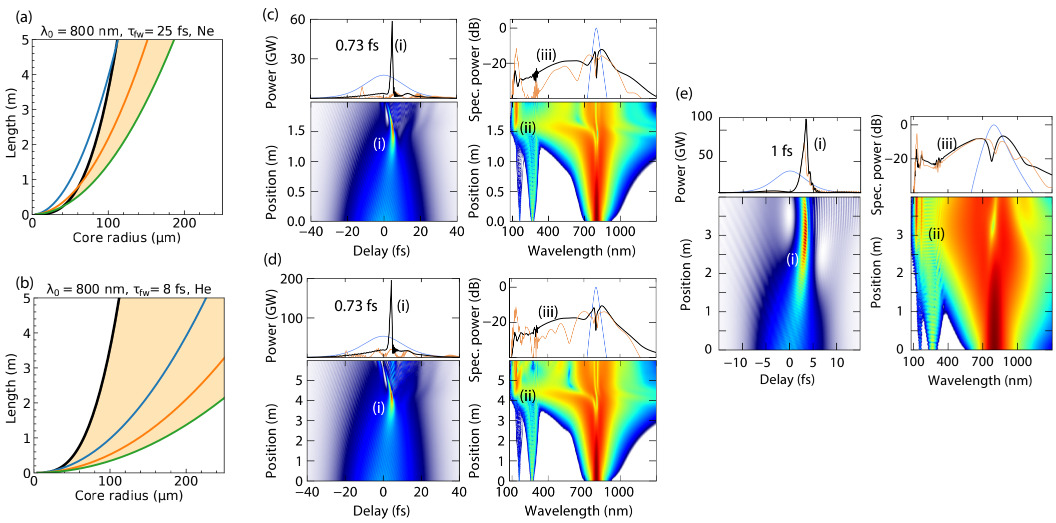

Fig. 1. (a,b) L_{fiss} (coloured curves) compared to L_{loss} (black curves) as a function of HCF core size a for (a) 25 fs pulses, (b) 8 fs pulses, and $\lambda_0 = 800$ nm. The yellow regions allow for soliton self-compression dynamics. The blue, orange and green curves are for λ_{zd} of 300 nm, 400 nm and 500 nm. (c,d) Numerical propagation simulations of high-energy soliton self-compression and fission in HCF for $\tau_{\text{fwhm}} = 25$ fs, $\lambda_0 = 800$ nm, $\lambda_{\text{zd}} = 350$ nm, $N = 6.5$. (c) $a = 80$ μm, 0.82 bar He gas and a pulse energy of 0.5 mJ. (d) $a = 140$ μm, 0.27 bar He gas and a pulse energy of 1.5 mJ. (e) Similar to (c,d) but for 5 fs pulse pumping. Points (i) indicate maximum self-compression, (ii) dispersive-wave emission, (iii) flat supercontinuum formation, extending to the VUV.

of parameters have been modelled and will be presented, these are just illustrative. In this case we show the self compression of a 25 fs pump pulse to 0.7 fs, with a peak power up to 200 GW. In both cases shown, λ_{zd}, λ_0, N and τ_0 are fixed and only a and the pump energy altered (from 0.5 to 1.5 mJ), showing that the dynamics scale extremely well to higher energies. Significant further scaling to the terrawatt regime is realistic in larger core HCF, and will be presented. Shorter pulse pumping (Fig. 1(e)) shows higher quality compression, with the generated 1 fs pulse having almost no pedestal. At the self-compression point, generation of a dispersive-wave at a resonant vacuum ultraviolet (VUV) frequency occurs. The energy transfer to the VUV can be extremely efficient, and we predict VUV pulse energies exceeding 50 μJ in sub-femtosecond pulses. Such a table-top light source has a brightness approaching that 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.

3. Experiments

Initial experimental results have been obtained [6], which support the theory and modelling in this paper.

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