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Scaling Optical Soliton Dynamics Over Twelve Orders of Magnitude: from One Watt Picosecond Pulses to Terawatt-Scale Sub-Femtosecond Pulses

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Abstract *Soliton dynamics can be scaled from the 1 W level in conventional fibres, to terrawatt peak powers in simple hollow capillaries. We model sub-femtosecond pulse self-compression, and experimentally demonstrate high-brightness multiple-μJ-scale ultraviolet (115-330 nm) pulse generation.*

Introduction

Bright optical soliton dynamics in waveguides were predicted by Hasegawa and Tappert in 1973[1], who were building on the pioneering work on optical solitons by Shabat and Zakharov[2]. In the first experimental demonstration of solitons in optical fibres[3], the soliton peak power was 1.24 W and the soliton duration was 7 ps. Subsequently, the soliton peak power has been considerably scaled, up to the sub-MW range in glass-core photonic-crystal fibres (PCF) fibres with extra large mode area[4].

In 2003, the use of microstructured PCF with a gas-filled hollow-core was demonstrated as a means to further scale the soliton energy and peak power, to the MW-scale. This started a new era in ultrafast nonlinear optics in gases, especially in anti-resonant guiding and kagome-style PCF[5–7], resulting in effects such as soliton self-compression at microjoule energies, leading to few-gigawatt peak powers[8–11], and efficient and tunable pulse generation in the deep (DUV) and vacuum ultraviolet (VUV) spectral region[8,9,12,13]. This scaling is a result of both the gas properties (lower nonlinearity and higher damage threshold than glass) and the scaling of the fibre mode area.

How much higher in energy and peak power can soliton dynamics be scaled? We have found that soliton dynamics can be harnessed in large-core (100 μm to 1 mm diameter) hollow capillary fibre (HCF), and that most of the ultrafast soliton effects demonstrated in recent years in gas-filled hollow-core PCF (HC-PCF), can be significantly scaled in energy by using HCF, by up to three orders of magnitude—resulting in terawatt peak powers.

Here we numerically and experimentally explore coherent soliton self-compression in HCF, 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.

Soliton Scaling in HCF

For bright temporal soliton dynamics, self-phase modulation (SPM) and negative group velocity dispersion (GVD) must act simultaneously, within the waveguide[1,2]. A pump pulse can be characterized by the soliton order $N = (L_\mathrm{d}/L_\mathrm{nl})^{1/2}$, where L_d is the dispersion length, and L_nl is the nonlinear length[14]. For higher order solitons ($N > 1$) the nonlinear SPM initially dominates, broadening the pulse spectrum. The resulting chirp is then compensated by the negative GVD, such that temporal compression of the pulse occurs[2,3,14]. This process is terminated when soliton fission occurs, due to higher-order linear and nonlinear effects[15–18]. One of these fission processes is RDW emission induced due to higher order dispersion[17–21], which can be used to produce a frequency tunable, ultrafast pulse source in the DUV and VUV[8,9,12,13].

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. 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 $L_\mathrm{fiss} = L_d/N$[15]. 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 HC-PCF fibres, the low guidance loss for small a allows one to achieve soli-

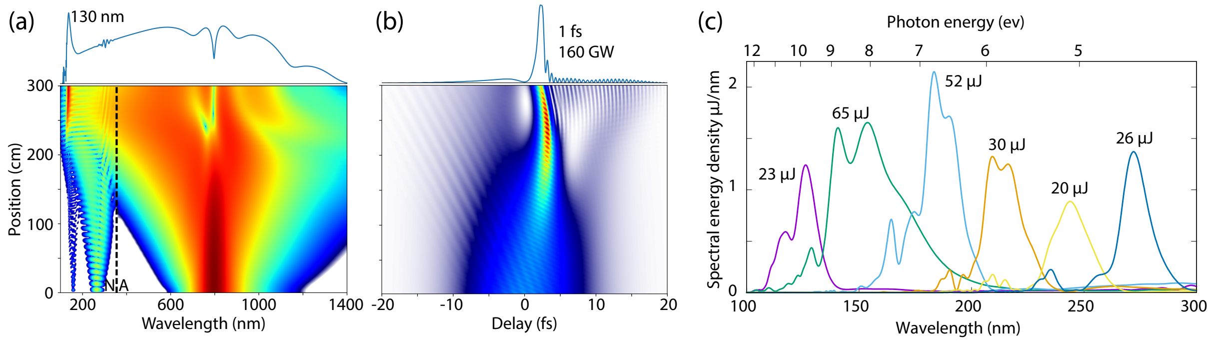

Fig. 1: Numerically modelled spectral (a) and temporal (b) evolution of a 10 fs, 800 nm, 0.5 mJ pump pulse in a 250 μm inner diameter HCF filled with 0.3 bar He. N, A indicate normal and anomalous dispersion regions. (c) Optimized VUV dispersive-wave emission peaks, for different He gas pressures.

ton 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.[22,23], we make use of 3 m long stretched capillary fibres, to provide sufficient propagation length for soliton dynamics to occur, while also pumping with 10 fs pulses from a conventional HCF compressor system to reduce L_{fiss}.

Numerical Results

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).

Experimental Results

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 μJ from 150 nm and longer wavelengths.

When fully scaled, this table-top light source will have a peak power exceeding current free-electron lasers 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.

Conclusions

In summary we have shown that soliton dynamics can be scaled by twelve orders of magnitude from thier initial demonstration in conventional fibres, at a peak power of 1 W, to self-compression and VUV generation at the terwatt scale in gas-filled hollow capillary fibres.

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References

[1] A. Hasegawa and F. Tappert, "Transmission of stationary nonlinear optical pulses in dispersive dielectric fibers. i.

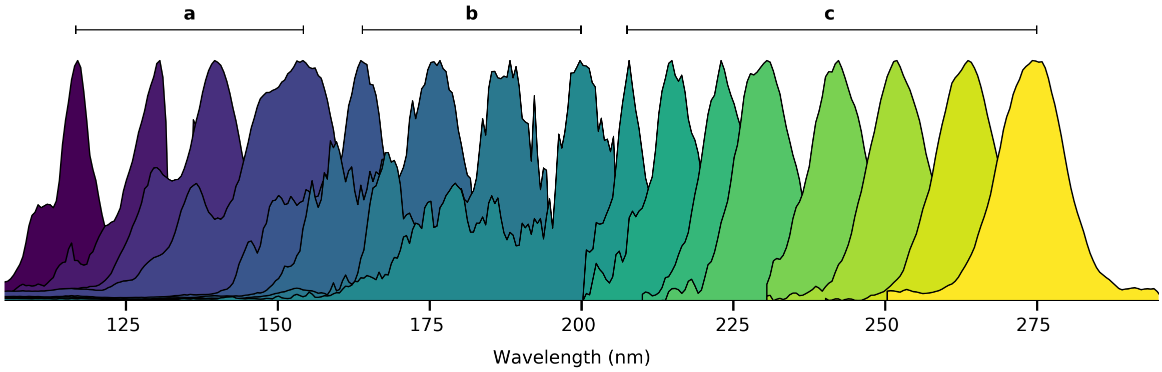

Fig. 2: Normalized experimental spectra obtained with ~ 10 fs pump pulses in a 3 m long, 250 µm inner-diameter capillary filled with He and Ne. (a) A pump energy of ~ 450 μJ in He gas, from left to right: 230 mbar, 350 mbar, 404 mbar, 550 mbar; (b) a pump energy of ~ 330 μJ in Ne gas, from left to right: 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.

anomalous dispersion," Applied Physics Letters, vol. 23, no. 3, pp. 142–144, 1973.

[2] A. Shabat and V. Zakharov, "Exact theory of two-dimensional self-focusing and one-dimensional self-modulation of waves in nonlinear media," Soviet physics JETP, vol. 34, no. 1, p. 62, 1972.

[3] L. F. Mollenauer, R. H. Stolen, and J. P. Gordon, "Experimental observation of picosecond pulse narrowing and solitons in optical fibers," Phys. Rev. Lett., vol. 45, pp. 1095–1098, Sep 1980.

[4] K. Wang and C. Xu, "Tunable high-energy soliton pulse generation from a large-mode-area fiber and its application to third harmonic generation microscopy," Applied Physics Letters, vol. 99, no. 7, p. 071112, 2011.

[5] J. C. Travers, W. Chang, J. Nold, N. Y. Joly, and P. S. J. Russell, "Ultrafast nonlinear optics in gas-filled hollow-core photonic crystal fibers s [invited]," J. Opt. Soc. Am. B, vol. 28, pp. A11–A26, Dec 2011.

[6] P. S. J. Russell, P. Hölzer, W. Chang, A. Abdolvand, and J. Travers, "Hollow-core photonic crystal fibres for gas-based nonlinear optics," Nature Photonics, vol. 8, no. 4, pp. 278–286, 2014.

[7] C. Markos, J. C. Travers, A. Abdolvand, B. J. Eggleton, and O. Bang, "Hybrid photonic-crystal fiber," Rev. Mod. Phys., vol. 89, p. 045003, Nov 2017.

[8] S.-J. Im, A. Husakou, and J. Herrmann, "High-power soliton-induced supercontinuum generation and tunable sub-10-fs vuv pulses from kagome-lattice hc-pcfs," Opt. Express, vol. 18, pp. 5367–5374, Mar 2010.

[9] N. Y. Joly, J. Nold, W. Chang, P. Hölzer, A. Nazarkin, G. K. L. Wong, F. Biancalana, and P. S. J. Russell, "Bright spatially coherent wavelength-tunable deep-uv laser source using an ar-filled photonic crystal fiber," Phys. Rev. Lett., vol. 106, p. 203901, May 2011.

[10] K. F. Mak, J. C. Travers, N. Y. Joly, A. Abdolvand, and P. S. J. Russell, "Two techniques for temporal pulse compression in gas-filled hollow-core kagomé photonic crystal fiber," Opt. Lett., vol. 38, pp. 3592–3595, Sep 2013.

[11] T. Balciunas, C. Fourcade-Dutin, G. Fan, T. Witting, A. Voronin, A. Zheltikov, F. Gerome, G. Paulus, A. Baltuska, and F. Benabid, "A strong-field driver in the single-cycle regime based on self-compression in a kagome fibre," Nature communications, vol. 6, p. 6117, 2015.

[12] K. F. Mak, J. C. Travers, P. Hölzer, N. Y. Joly, and P. S. J. Russell, "Tunable vacuum-uv to visible ultrafast pulse source based on gas-filled kagome-pcf," Opt. Express, vol. 21, pp. 10942–10953, May 2013.

[13] A. Ermolov, K. F. Mak, M. H. Frosz, J. C. Travers, and P. S. J. Russell, "Supercontinuum generation in the vacuum ultraviolet through dispersive-wave and soliton-plasma interaction in a noble-gas-filled hollow-core photonic crystal fiber," Phys. Rev. A, vol. 92, p. 033821, Sep 2015.

[14] G. P. Agrawal, Nonlinear fiber optics. Academic press, 2007.

[15] J. M. Dudley, G. Genty, and S. Coen, "Supercontinuum generation in photonic crystal fiber," Rev. Mod. Phys., vol. 78, pp. 1135–1184, Oct 2006.

[16] P. Beaud, W. Hodel, B. Zysset, and H. Weber, "Ultrashort pulse propagation, pulse breakup, and fundamental soliton formation in a single-mode optical fiber," IEEE Journal of Quantum Electronics, vol. 23, pp. 1938–1946, Nov 1987.

[17] Y. Kodama and A. Hasegawa, "Nonlinear pulse propagation in a monomode dielectric guide," IEEE Journal of Quantum Electronics, vol. 23, pp. 510–524, May 1987.

[18] A. V. Husakou and J. Herrmann, "Supercontinuum generation of higher-order solitons by fission in photonic crystal fibers," Phys. Rev. Lett., vol. 87, p. 203901, Oct 2001.

[19] P. K. A. Wai, C. R. Menyuk, Y. C. Lee, and H. H. Chen, "Nonlinear pulse propagation in the neighborhood of the zero-dispersion wavelength of monomode optical fibers," Opt. Lett., vol. 11, pp. 464–466, Jul 1986.

[20] N. Akhmediev and M. Karlsson, "Cherenkov radiation emitted by solitons in optical fibers," Phys. Rev. A, vol. 51, pp. 2602–2607, Mar 1995.

[21] M. Erkintalo, Y. Q. Xu, S. G. Murdoch, J. M. Dudley, and G. Genty, "Cascaded phase matching and nonlinear symmetry breaking in fiber frequency combs," Phys. Rev. Lett., vol. 109, p. 223904, Nov 2012.

[22] T. Nagy, M. Forster, and P. Simon, "Flexible hollow fiber for pulse compressors," Applied Optics, vol. 47, pp. 3264–3268, June 2008.

[23] T. Nagy, V. Pervak, and P. Simon, "Optimal pulse compression in long hollow fibers," Opt. Lett., vol. 36, pp. 4422–4424, Nov 2011.