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Broadband Ultraviolet Generation with 50% Conversion Efficiency in Hollow Capillary Fibers

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Abstract: We demonstrate broadband wavelength up-conversion (240–320 nm) based on a seeded four-wave mixing scheme in gas-filled stretched hollow-capillary fibers with 50% conversion efficiency. Our technique is scalable in energy from the nJ to mJ level.

Hollow fibers provide an energy scalable platform for intensity dependent nonlinear effects in gases [1], such as self-induced phase modulation [2], and soliton driven effects, such as temporal self-compression to sub-femtosecond pulses and resonant dispersive wave (RDW) emission across the vacuum (VUV) and deep ultraviolet (DUV) [3]. Here, we focus on a seeded four-wave mixing (FWM) scheme in stretched hollow capillary fibers (HCF) in order to boost the up-conversion efficiencies to the ultraviolet spectral region and offer a clear route for arbitrary control of temporal and spectral shape. In contrast to RDW emission, FWM does not require temporal pre-compression of the driving fields, as shown in pioneering works in rigid hollow capillary fiber (HCF) with mJ chirped pulses [4], as well as more recently in hollow-core PCF pumped with unchirped 100 fs long pulses with sub-μJ energies [5]—readily available from current high-average power laser systems.

In this contribution we demonstrate three key results targeting the deep ultraviolet. Firstly, we show that the FWM process can be arbitrarily scaled up and down in energy in HCF simply by changing the hollow-core diameter (d) and appropriately adjusting the gas pressure to compensate both the linear and nonlinear phase-mismatch [6]. Fig. 1 and Fig. 2 show typical experimental results obtained respectively in a small stretched capillary (d = 50 μm, 5.5 cm long), and in a larger stretched capillary (d = 150 μm, 135 cm long). Secondly, we demonstrate a record high conversion efficiency, with 50% of the input pump energy directly converted into a broad and coherent spectral band centred in the DUV (Fig. 1c,d). Thirdly, we investigate the role of the seed and pump energy in order to achieve either a record high pulse energy of 70 μJ in the large capillary setup (Fig. 2g), or the generation of a nearly transform-limited 8 fs pulse tuneable across the 255–290 nm band (Fig. 2b-f), despite using a fixed two-color pumping scheme. In all of these experiments we use the second harmonic and fundamental of a 1 kHz Ti:Sapphire amplified laser centered at 800 nm as pump and seed respectively, with pulse durations of 35 fs and 45 fs at the fiber input, and the same linear polarization.

The gas filling pressure, and pump and seed energies all drastically alter the generation process and the up-conversion efficiencies. The self- and cross- nonlinear phase-shift induced by raising the pump (seed) energy

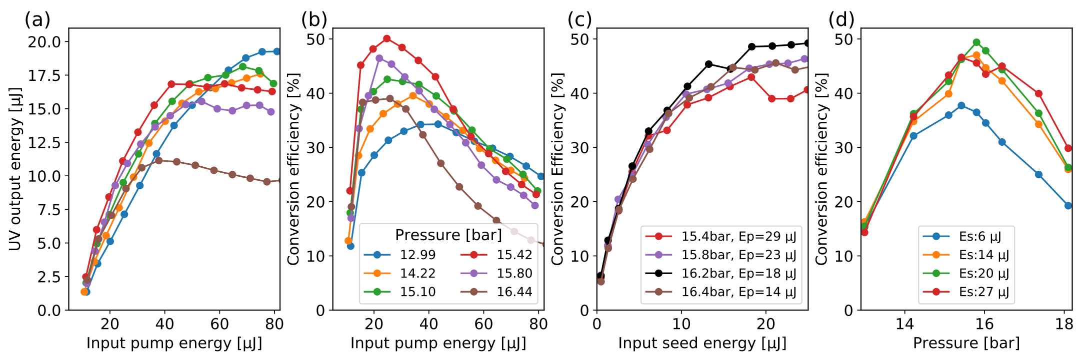

Fig. 1. **Small capillary**: (a,b) The pulse energy (a) and conversion efficiency (b) of the generated UV at the fiber output as function of the input pump energy for different He pressures when seeding with 16 μJ. (c) The energy conversion efficiency as a function of the input seed energy for selected He pressures and pump energies. (d) The energy conversion efficiency as a function of gas pressure for a fixed pump energy of 25 μJ.

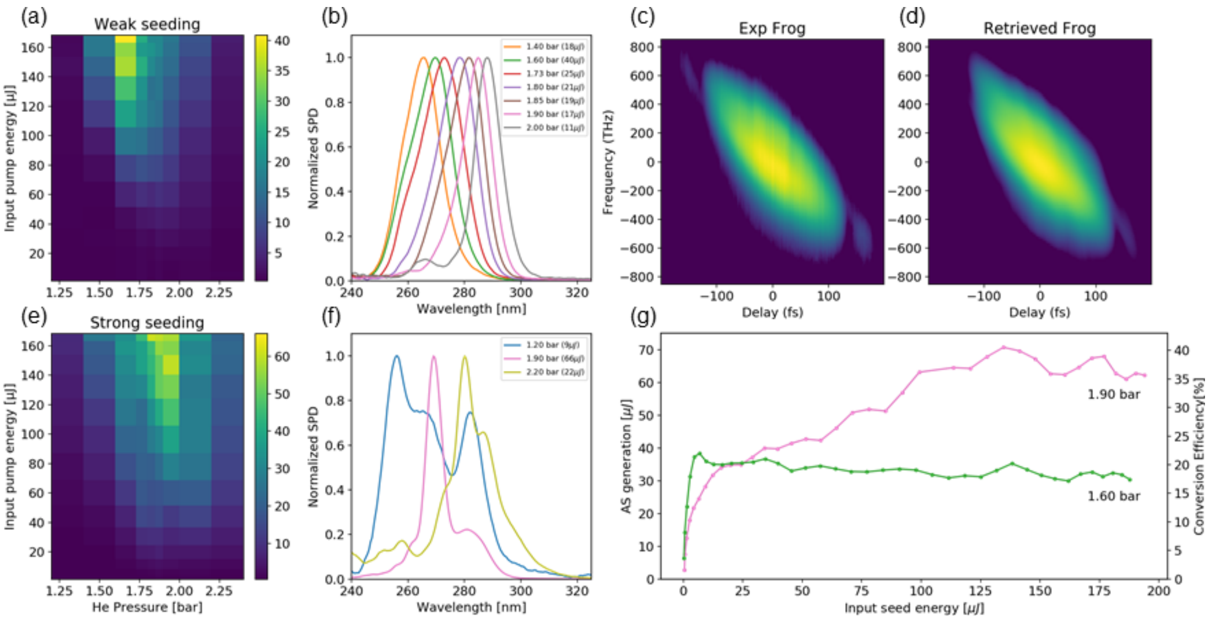

Fig. 2. **Large capillary**: (a,e) Pseudo color maps of the experimentally generated UV energy, when using a weak seed of 2 μJ (a) and strong seed of 115 μJ (e), as function of the input pump energy and He pressure. (b,f) Spectral tuning in the weak (b) and strong (f) seed regime at different gas pressures and pump energies chosen to maximise the UV energy as shown in the legend. (c) Measured and (d) retrieved self-diffraction FROG traces of the UV pulse in the weak seed regime, supporting a pulse duration of 8 fs at the fiber output end (the spectrum supports a 7.7 fs transform limited duration). (g) UV pulse energy and conversion efficiency as a function of the input seed energy at the maximum pump energy investigated in this work (170 μJ) and optimal pressures of 1.6 and 1.9 bar for the weak and strong seed cases.

can be balanced out to a great extent by decreasing (increasing) the gas pressure. At low seed energy (Es), the nonlinear phase shift driven by the seed is negligible and the maximum UV generation shifts towards lower He pressures as the pump energy is raised (see Fig. 1a,b and Fig. 2a). On the other hand, for higher seed energies the optimal conversion efficiency (parametric gain) shifts towards larger He pressures for a given pump energy. This is highlighted in Fig. 1c,d and Fig. 2e by varying the input seed energy and by a direct comparison in Fig. 2g.

We anticipate a much wider frequency tuneability and direct phase-transfer [7] to the DUV and VUV through an external and dedicated seed beam line, as well as further energy scaling up to the ~mJ level by using larger and longer HCF, which will open several more applications, e.g. in large-scale free-electron facilities [8].

References

1. C. M. Heyl et al., "Scale-invariant nonlinear optics in gases," Optica **3**, 75–81 (2016).
2. M. Nisoli et al., "Generation of high-energy 10-fs pulses by a new pulse compression technique," in *Conference on Lasers and Electro-Optics,* (Optical Society of America, 1996), p. CTuR5.
3. J. C. Travers, T. F. Grigorova, C. Brahms, and F. Belli, "High-energy pulse self-compression and ultraviolet generation through soliton dynamics in hollow capillary fibres," Nat. Photonics **13**, 547–554 (2019).
4. J. Wojtkiewicz et al., "Chirped-pulse frequency conversion of ultrafast pulses to the deep-UV," in *(CLEO). Conference on Lasers and Electro-Optics, 2005.*, (IEEE, Baltimore, MD, USA, 2005), pp. 186–188 Vol. 1.
5. F. Belli, A. Abdolvand, J. C. Travers, and P. S. J. Russell, "Highly efficient deep UV generation by four-wave mixing in gas-filled hollow-core photonic crystal fiber," Opt. Lett. **44**, 5509–5512 (2019).
6. G. Cappellini and S. Trillo, "Third-order three-wave mixing in single-mode fibers: exact solutions and spatial instability effects," JOSA B **8**, 824–838 (1991).
7. J. P. Siqueira et al, "Spectral phase transfer from near IR to deep UV by broadband phase-matched four-wave mixing in an argon-filled hollow core waveguide," J. Phys. B: At. Mol. Opt. Phys. **49**, 195601 (2016).
8. R. Marsh et al, "Performance of a second generation X -band rf photoinjector," Phys. Rev. Accel. Beams **21**, 073401 (2018).