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# Dispersion tuning of nonlinear dynamics in gas-filled capillary fibres

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## ABSTRACT

We present experimental results on tuning the zero-dispersion wavelength at the pump wavelength in gas-filled capillary fibre, which has dramatic effect on the observed nonlinear dynamics. We pump an argon-filled hollow capillary fibre, with inner diameter of 250  $\mu\text{m}$  and a length of 3 m with 10 fs pulses at 800 nm. By changing the gas pressure, it is possible to tune the zero-dispersion wavelength compared to the pump wavelength so that different nonlinear regimes are accessed. For anomalous pump dispersion typical soliton and soliton-plasma dynamics are observed, such as self-compression, dispersive-wave emission, soliton blue-shifting and ionization-induced pulse splitting. Normal pump dispersion leads to the generation of supercontinua over 3 octaves broad and emission of dispersive-waves in high-order modes.

**Keywords:** nonlinear fibre optics, soliton dynamics, self-phase-modulation, dispersion, supercontinuum generation, dispersive-wave emission

Hollow-core fibres have been used as a system for studying nonlinear effects in gases for many years because of the advantages of extended interaction lengths and the ability to control the dispersion and nonlinearity through the gas pressure. In the previous decade many breakthroughs were made using hollow-core photonic crystal fibre (HC-PCF) due to their strong anomalous waveguide dispersion<sup>1</sup>. However, they possess guidance resonances, which can complicate the observed nonlinear dynamics, and their small core sizes restrict energy scaling. Recently, soliton dynamics have also been proven to be accessible in hollow capillary fibres (HCF)<sup>2</sup>, in which guidance resonances are absent and the large core sizes allow significant energy scaling of soliton effects at the cost of extended fibre lengths, which have become accessible with the development of the fibre stretching technique<sup>3</sup>.

The frequency dependent group velocity dispersion (GVD) profile is key to the nonlinear dynamics experienced by an ultrafast pulse propagating in a gas-filled fibre. When the pump pulse wavelength is in the anomalous (negative) GVD region, the dispersion can continuously balance the self-phase modulation (SPM) induced chirp along the fibre length, leading to the formation of optical solitons. When it is in the normal GVD region, the dispersion arrests SPM broadening. A reasonable way to parametrise the dispersion landscape in fibres is through the zero-dispersion wavelength (ZDW), which is the wavelength at which the GVD is equal to zero. In gas-filled hollow core fibres there are two contributions to the GVD—one due to the waveguide and one due to the filling gas. Since the waveguide dispersion of an evacuated capillary fibre is anomalous and the filling gas dispersion is normal in the visible range, wavelengths shorter than the ZDW will be in the normal dispersion regime, while wavelengths longer than the ZDW will be in the anomalous regime.

Here we experimentally demonstrate that by changing the pressure of the filling gas, hence the dispersion landscape in which an ultrafast pulse propagates, a wide range of different nonlinear dynamics can be observed in long stretched HCF pumped with short pump pulses. For the following experimental results 3 W, 26 fs pulses at 800 nm, produced by a commercial Ti:Sapphire oscillator and amplifier system (Coherent Legend Elite Duo USX), were broadened by SPM in a 450  $\mu\text{m}$  inner diameter, 1.6 m long stretched HCF, and filled with 2.2 bar helium, and compressed using chirped-mirrors (PC70, Ultrafast Innovations) and a pair of BK7 wedges (Femtolasers), to 10 fs transform-limited pulses. The power at the output of the compressor was controlled by a broadband  $\lambda/2$  wave-plate and Brewster reflection off a silicon plate, giving a maximum output of 1.1 W. These pulses were coupled into a second HCF with inner diameter of 250  $\mu\text{m}$  and a length of 3 m, filled with different argon pressures from 7 to 3344 mbar, which tune the ZDW from 300 nm to 1300 nm. At each pressure the input energy was varied and the output spectra recorded with 2 calibrated spectrometers connected to an integrating sphere. The coupling efficiency was estimated from the vacuum transmission of the second HCF stage.

Fig. 1 shows measurement of the output spectrum for changing the coupled energy in the fibre. For a ZDW tuned sufficiently away from the pump wavelength, such that the pump is in the anomalous dispersion regime, the evolution is that of typical soliton dynamics influenced by plasma formation. After the soliton self-compression point (corresponding

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to the point of maximum spectral expansion), blue-shifting soliton dynamics<sup>4</sup> can be observed in Fig. 1a and Fig. 1b (ZDW of 400 nm and 450 nm respectively). In Fig. 1a a clean blue soliton shift is identifiable, whereas in Fig. 1b, pulse splitting occurs—identified by the fringes in the blue shoulder. Similar dynamics, but with additional deep ultraviolet dispersive-wave emission can be seen in Fig. 1c, where the ZDW is tuned up to 500 nm. Further tuning of the ZDW to 650 nm shifts the phase-matching wavelength for the dispersive-wave up to around 400 nm (Fig. 1d), and a significant soliton recoil into the infrared up to 1400 nm can be observed at this point, as well as dispersive-wave emission in higher-order modes around 260 and 220 nm.

On the other hand, tuning the ZDW to coincide with the pump wavelength as in Fig. 1e leads to the generation of a very broad supercontinuum (spanning 200 nm to beyond 1600 nm). This continuum becomes flatter and broader for a ZDW of 950 nm (Fig. 1f), before the normal dispersion at the pump begins to restrict the SPM and self-steepening dominated nonlinear broadening at higher gas pressures and longer ZDWs. At this point the coupled peak power is exceeding the critical power for self-focusing<sup>5</sup>, and spatial nonlinear dynamics are occurring. Understanding these effects in detail requires use of our fully vectorial multimode numerical simulations<sup>2</sup>, which are ongoing and will be presented at the conference.

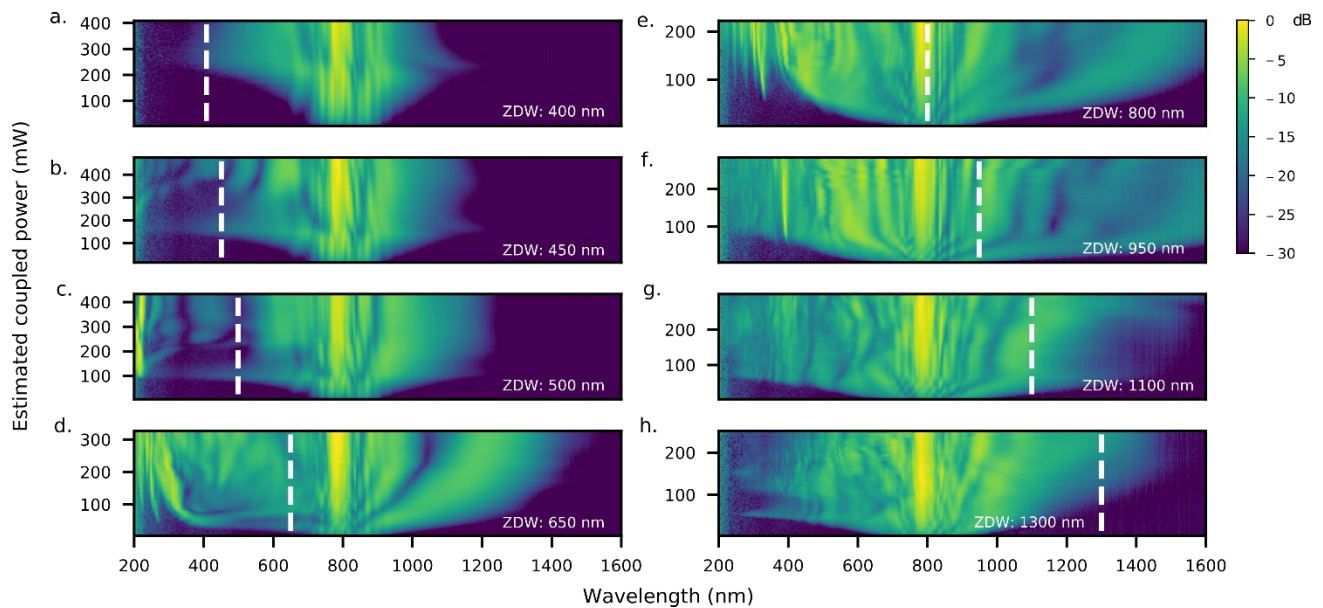


Figure 1. Experimental output spectra generated by 10 fs, 800 nm pump pulses, as a function of coupled power in the second HCF stage (3 m long, 250  $\mu\text{m}$  inner diameter), with the argon pressure tuned accordingly for the indicated ZDW: a. 28 mbar, b. 43 mbar, c. 66 mbar, d. 199 mbar, e. 467 mbar, f. 940 mbar, g. 1703 mbar, h. 3344 mbar.

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