Combined soliton pulse compression and plasma-related frequency up-conversion in gas-filled photonic crystal fiber

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We numerically investigate self-frequency blue-shifting of a fundamental soliton in a gas-filled hollow-core photonic crystal fiber. Because of the changing underlying soliton parameters, the blue-shift gives rise to adiabatic soliton compression. Based on these features, we propose a device that enables frequency shifting over an octave and pulse compression from 30 fs down to 2.3 fs.

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Hollow-core photonic crystal fibers (PCFs) have made it possible to transfer gas-based nonlinear optics to small-core optical fibers [1]. PCF-based systems combine the merits of conventional fibers, such as tight mode confinement over long interaction lengths and precise control over the dispersion profile, with the advantages of gases, where material breakdown does not amount to a permanent damage and transparency can be achieved even in extreme wavelength ranges. In the case of kagomé PCF [2], these features have been harnessed to observe high-power supercontinua [3], pulse propagation in Raman free, highly nonlinear materials [4], and efficient wavelength-tunable UV generation [5,6].

Recently we introduced the new regime of ionization-based nonlinear fiber optics, where soliton self-compression can lead to intensities sufficient to partially ionize the filling gas, and a subsequent soliton self-frequency blue-shift results from the free-electron induced phase-modulation [7,8]. The dynamics of those results were dominated by the initial stage of higher order soliton propagation and compression, and the emission of multiple self-frequency blue-shifting solitons. However, perturbation theory predicted a clear fundamental soliton self-frequency blue-shift without the complication of any other higher order nonlinear effects [8]. In this Letter we show numerically that such a clean shift can occur, and demonstrate how it can be utilized in an all-fiber integrated device for frequency conversion over an octave, together with simultaneous pulse compression to single-cycle durations.

Pivotal to the device operation are the unique features of kagomé PCF. A representative cross-sectional structure is shown in the inset of Fig. 1. These fibers exhibit transmission window wide enough to contain even few cycle pulses [2]. In addition, due to the low modal overlap with the glass structure, these fibers can handle high pulse energies [1]. Most importantly when evacuated they offer low, but anomalous, group-velocity dispersion (GVD, β_2) over a wide wavelength range, thus facilitating soliton dynamics. When filled with gas, the GVD of the system can be precisely adjusted through a proper choice of gas pressure and species. Following [9], the fiber contribution to the dispersion can be approximated by an expression originally proposed for capillary fibers [10]. Fig. 1 shows the calculated GVD curve for a kagomé PCF with a core diameter of 18 μm filled with 5 bar of argon – showing broadband anomalous dispersion.

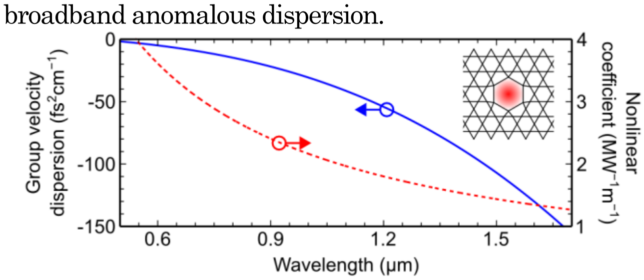

Figure 1: Broadband anomalous GVD (solid-line) and nonlinear coefficient (dashed-line) of a 18 μm core fiber filled with 5 bar of Ar. The inset shows the cross-section of an ideal kagomé PCF.

In order to study soliton dynamics in the ionization regime numerically, an established uni-directional field propagation equation can be used [11–14]:

$$\partial_z E(z,\omega) = i(\beta(\omega) - \omega/v)E(z,\omega) + i\frac{\omega^2\mu_0}{2\beta(\omega)}\mathcal{F}\left\{\varepsilon_0\chi^{(3)}E(z,t)^3\right\} - \frac{\omega\mu_0}{2\beta(\omega)}\mathcal{F}\left\{\partial_t n(z,t)\frac{I_p}{E(z,t)} + \frac{e^2}{m_e}\int_{-\infty}^{t} n(z,t')E(z,t')dt'\right\} \qquad (1)$$

where z is the propagation distance in the fiber, t the time in a frame moving at a suitable reference velocity v, ω the angular frequency in rad.s^{-1} and $E(z,\omega)$ the field in the spectral domain, which is given by taking the Fourier transform of the real electric field strength, i.e. $E(z,\omega) = \mathcal{F}\{E(z,t)\}$. The linear dispersion of modes of kagomé PCF is given by $\beta(\omega)$. The second term accounts for third-order nonlinearities where $\chi^{(3)}$ is the third-order susceptibility. ε_0 and μ_0 are the permittivity and permeability of free space. The final term represents the influence of photoionization [15] – namely $n(z,t)$ is the time-varying free-electron density; I_P is the first ionization energy; and e and m_e are the charge and mass of an electron. The underlying ionization rate is calculated using a model developed by Ammosov et al. [16]; we have verified that the alternative Yudin-Ivanov model [17] produces little significant difference for our parameters. As in the case of solid-core fiber, soliton dynamics arise from the interplay between dispersion and a Kerr-based nonlinearity. In addition, the pulse can be subject to ionization effects provided the pulse intensity is high enough. The instantaneous generation of free electrons causes the refractive index to drop, imposing a phase modulation [7] that is however asymmetric as the reverse process of recombination occurs on time-scales longer than the pulse duration. In the spectral domain, this phase-modulation produces a frequency up-shift [18].

The proposed device was designed to convert light from one important laser wavelength (1500 nm, Er-doped fiber lasers) to another one (800 nm, Ti:sapphire lasers), although this technique can be adapted to other wavelengths. The parameters below are perfectly amenable to experimental realization, for example with optical parametric amplifiers or fiber laser systems. In this study, the pump is centered at 1500 nm with a 30 fs full-width at half maximum (FWHM) duration transform-limited pulse and 1.7 μJ energy – corresponding to a peak power of 50 MW (peak intensity of 41 TW/cm^2). The launched pulse has a soliton number of $N = (\gamma P_0 t_0^2 / |\beta_2|)^{0.5} \approx 1.4$.

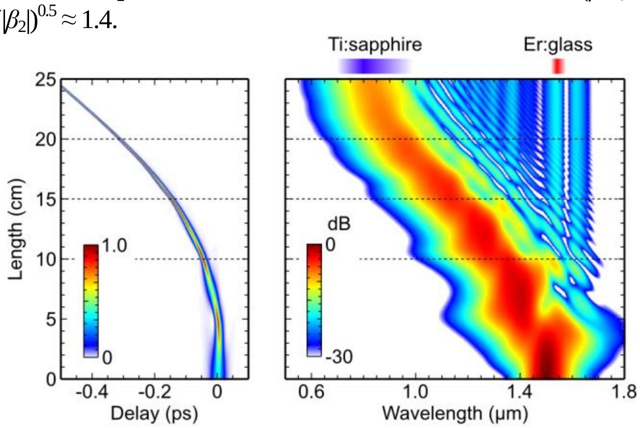

Figure 2: Temporal (left) and spectral (right) evolution during propagation. The main wavelength is converted from 1500 nm to ~800 nm.

Figure 2 presents the spectral and temporal evolution of the pulse along 25 cm of the fiber. Most of the pulse energy undergoes a coherent spectral blue-shift from a wavelength of 1500 nm, and eventually reaching a center wavelength of 815 nm with a conversion efficiency of 30%. This self-frequency shifting of a soliton is redolent of the more widely known Raman effect, but contrary in sign [8]. The remaining energy is transferred to linear modes around the original pump wavelength or lost in the ionization process. Frequency-shifting kicks in at around 4 cm where the pulse has gained sufficient intensity to ionize the gas. Pulses with non-integer soliton number shed excess energy into linear modes, simultaneously adjusting their peak power and pulse duration to converge to a soliton. As a result of starting with $N > 1$, the pulse initially undergoes a slight temporal compression and hence reaches an enhanced peak intensity. From this point on the pulse is influenced by the presence of a time-varying free-electron density which causes a continuous blue-shift over the following 20 cm. In the temporal domain, this is accompanied by a considerable reduction in pulse duration. Both the blue-shifting and the compression cease when the ionization-induced losses have caused the peak intensity to drop to levels insufficient for ionization. Further insight into the frequency shift and pulse compression can be observed in the sequence of cross-correlation frequency-resolved optical gating traces shown in Fig. 3. The almost chirp-free output pulse has an energy of 542 nJ, and a FWHM duration of 4 fs, corresponding to ~1.5 optical cycles.

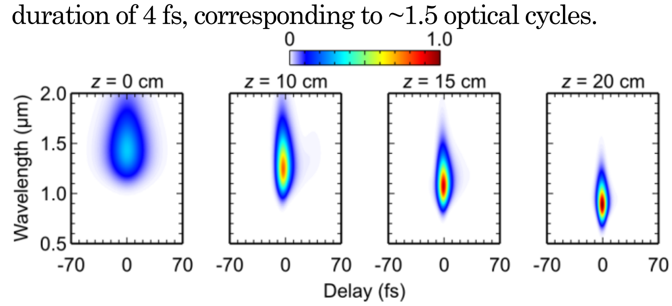

Figure 3: Cross-correlation frequency-resolved optical gating traces (at the positions marked with dashed-lines in Fig. 2) showing the pulse compression and frequency shifting.

The physics behind the compression is closely related to adiabatic pulse compression [19], with the important difference that, due to the ionization losses, the pulse energy is not conserved. Adiabatic soliton compression in hollow-core PCFs was investigated theoretically in [20], by considering the fiber-gas system to be axially varying, which could be achieved using a negative pressure gradient to produce an axially-decreasing dispersion. In our system, however, the pressure is invariant with position and the propagating medium remains the same along the fiber length. Instead, the soliton perceives decreasing dispersion and increasing nonlinearity due to its increasing center frequency. As a result it compresses while undergoing the self-frequency blue-shift. For a shift from 1500 nm to 815 nm the magnitude of β_2 reduces by a factor of 6.54, and the nonlinear coefficient increases by a factor of 1.84. This suggests a compression factor of 12 in a lossless case. Photoionization-induced losses over the entire propagation distance cause ~70% energy loss, reducing this factor to ~7.5. Mamyshev et al. observed adiabatic soliton compression that is analogous but opposite in sign to our results [21]. Namely, the Raman-induced soliton self-frequency downshift resulted in the soliton's perceiving decreasing dispersion in a single-mode silica fiber with an inverse parabolic dispersion profile. However, a small Raman-induced frequency shift (1.57 to 1.62 μm) and a lower effective nonlinearity due to the frequency downshift resulted in a relatively small compression factor (95 to 55 fs).

It is worth noting some differences from the results reported in [7], where the process was pumped at 800 nm. In that case soliton numbers of 5 to 9 were required to reach sufficient intensities, whereas here the blue-shifting dynamics of a fundamental soliton can be studied. In Fig. 4a it can be seen how a soliton under the influence of ionization oscillates around $N = 1$. Comparing the precise dynamics of ionization in both systems reveals that in the previous study the frequency shift occurs as an abrupt process whereas in this work the blue-shifting is rather continuous and prolonged. At the point of initial ionization the free-electron density is lower, allowing for lower ionization losses at the initial stages of propagation, which helps perpetuate the process over longer distances (Fig. 4b). In addition, in this case the pump wavelength is located farther away from the zero dispersion wavelength which allows for a bigger frequency shift towards the blue. Note that the abrupt changes in soliton number plotted in Fig. 4a are caused by the small center frequency jumps seen in Fig. 2. They coincide with the peaks of maximum free-electron density shown in Fig. 4b suggesting that most of the frequency shift during each cycle of compression and ionization occurs around these peaks.

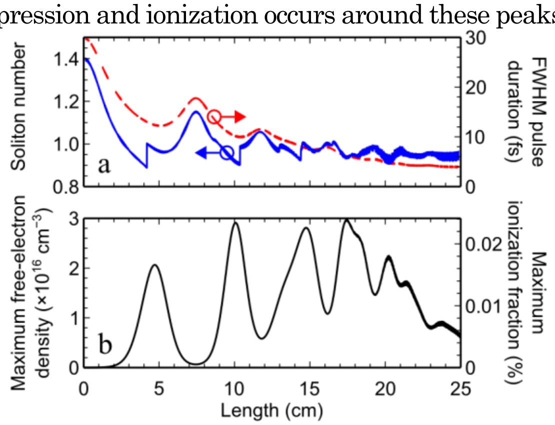

Figure 4: (a) Evolving soliton number and FWHM pulse duration as a function of propagation distance. (b) Maximum free-electron density and ionization fraction along propagation.

We can further exploit the advantages of gas-based systems, and tune the frequency shift by changing the pressure at the output end of the fiber. This introduces a pressure gradient which allows a control over the axially varying optical properties without disturbing too much the initial dynamics. At equilibrium, the pressure distribution along the fiber is given by [22]:

$$P(z) = \sqrt{P_0^2 + \frac{z}{L}\left(P_L^2 - P_0^2\right)}, \tag{2}$$

where z is the position along the fiber length L; P_0 and P_L are the pressure at the input and output end of the fiber. Figure 5 shows the pulse spectra and the durations when the output pressure is varied from 2 to 7 bar. By applying a positive pressure gradient, the wavelength can be tuned down to 720 nm while achieving a compression factor of 13, resulting in a pulse duration of ~2.3 fs.

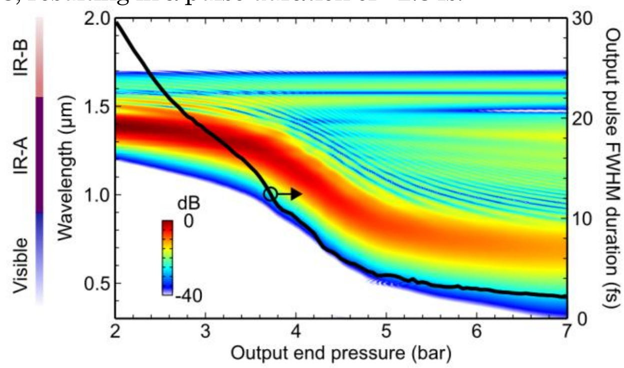

Figure 5: Output pulse spectra and FWHM durations (solid-line) as a function of end gas cell pressure.

These results might be useful for a combined frequency up-shifter/pulse-compressor for fs-pulses in the few-μJ energy range. In contrast to the more conventional method of using second harmonic generation (SHG), this technique is perfectly suited for high-intensity ultra-short pulses. In addition, the output frequency can be precisely tuned within the maximum achievable frequency up-shift by adjusting the fiber length, pump energy or the pressure gradient. The proposed system in combination with high power fiber lasers might present a potential replacement of ultrafast Ti:sapphire laser systems. It could offer pulse energies of several hundreds of nJ at repetition rates of several MHz, pulse durations shorter than those that have been achievable with the best oscillators, and unrivalled compactness and robustness.

In conclusion, fundamental soliton propagation in the ionization regime has been studied numerically. Through proper choice of parameters, a single soliton can remarkably undergo a prolonged and continuous self-frequency blue-shift. These dynamics may prove useful for realizing a combined frequency-converter and pulse-compressor for fs-pulses in the few-μJ energy range.

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