Optimal pulse compression in long hollow fibers

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The spectral broadening performance of 1 m and 3 m long hollow fibers are compared. The 3 m capillary clearly outperforms the 1 m one in terms of both transmission and achievable spectral broadening. Starting from 1.1 mJ 71 fs pulses at 780 nm, a spectral broadening ratio of 26 was achieved using a single 3 m long argon-filled hollow fiber. After compression the measured pulse duration was 4.5 fs corresponding to a compression ratio of 16 at an energy of 0.42 mJ. Both the pulse duration and the pulse energy were limited by the applied chirped mirrors. © 2011 Optical Society of America

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Current lasers delivering few-cycle pulses (<5 fs) at the mJ energy level play a prominent role in contemporary ultrafast science [1,2]. Such short pulses have very broad spectra, well beyond the gain bandwidth of conventional amplifying media. Therefore these lasers incorporate a compression stage where the spectrum of the amplified pulses is broadened via nonlinear optical effects—most frequently by self-phase modulation (SPM). Since its invention, the hollow fiber technique [3,4] has become the standard method for spectral broadening of energetic ultrashort pulses. Although other compression schemes exist, e.g. self-guided propagation in filaments [5,6] or SPM in planar waveguides [7], the main advantage of using hollow fibers is the excellent beam quality [8] and spectral homogeneity across the beam profile. This enables a high quality pulse compression which is essential for most applications.

Although hollow fibers are typically used for the compression of sub-mJ pulses, techniques were also developed to extend the pulse energy to the multi-mJ level, e.g. using circularly polarized light in the waveguide which increases the ionization threshold and allows higher intensities [9]. Another very efficient approach is the pressure gradient method, in which the front side of the hollow fiber is evacuated and noble gas is applied to the end of the capillary. In this manner self-focusing is prevented in front of the capillary maintaining optimal beam coupling into the waveguide [10,11].

Since the spectral broadening in noble-gas-filled hollow fibers is mostly governed by SPM, it is characterized by the accumulated nonlinear phase or B-integral. For $B > 5$ the spectral broadening factor ($F = \Delta\omega_{\mathrm{out}}/\Delta\omega_{\mathrm{in}}$) is approximately proportional to the B-integral [12]:

$$F = \sqrt{1 + \frac{4}{3\sqrt{3}}B^2} \sim B, \quad \text{where } B = k_0 \int_0^L n_2 I(z)\mathrm{d}z. \tag{1}$$

Here $k_0 = 2\pi/\lambda_0$ is the wave number, n_2 denotes the nonlinear refractive index of the medium, I is the light intensity and L is the length of the medium. According to the design criteria of hollow fiber compressors outlined in [13], (i) the peak power of the pulse should not exceed the level of the critical power of self-focusing ($P_{\mathrm{cr}} \sim \lambda^2/n_2$). This poses an upper limit on n_2 and practically determines the gas type and the maximal pressure. (ii) The peak intensity should not exceed a threshold where photoionization becomes non-negligible (the nonlinear phase shift introduced by the free electrons emerging from ionization is comparable to that due to Kerr effect). In practice, this sets a lower limit to the inner diameter (ID) of the hollow fiber. (iii) In order to maintain good-quality waveguides, the length of the hollow fibers is limited to ~1 m due to technological limitations of the rigid hollow fibers. All these criteria severely limit the spectral broadening capability of the hollow fiber compressor. To the best of our knowledge the highest compression ratio achieved until now did not exceed a factor of 14 [3].

Recently, a hollow fiber assembly incorporating a stretched flexible capillary [14] was introduced showing ideal waveguide properties at arbitrary length. In this case (iii) can be reformulated so the length of the nonlinear interaction is only limited by the available lab space. This gives an extra degree of freedom for the design of such compressors and can influence the optimization process.

In this Letter we demonstrate that the long stretched flexible hollow fibers are superior to hollow fibers of standard size in terms of both the achievable spectral broadening and the transmission.

A given spectral broadening (or equivalently B-integral) can be achieved by different fiber geometries: either short fibers with small ID, or long fibers with large ID can be used. If (i) and (ii) are fulfilled (low intensity regime) then $I(z) = I_0 \exp(-\alpha z)$ and the B-integral can be analytically evaluated:

$$B = k_0 n_2 I_0 \frac{1 - \exp(-\alpha L)}{\alpha} = \frac{k_0 n_2 I_0}{\alpha} A, \tag{2}$$

where α is the linear loss coefficient and $A = 1 - T$ is the overall propagation loss of the waveguide. Taken into account that $\alpha \sim \lambda^2/\mathrm{ID}^3$ and $I_0 \sim 1/\mathrm{ID}^2$, we get for a given B-integral:

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$$A \sim \frac{B\lambda^3}{n_2 \mathrm{ID}} \text{ with a fiber length of } L \sim \frac{\mathrm{ID}^3}{\lambda^2}(1-A). \quad (3)$$

According to (3), in order to achieve a given B-integral it is advantageous to use long fibers with large ID because the linear loss is inversely proportional with the ID. Consequently, considerably larger spectral broadening can be achieved with higher transmission by using large diameter, long hollow fibers.

For the experiments a standard Ti:sapphire CPA system was used delivering 1.1 mJ pulses of 71 fs transform limited duration at 780 nm with a repetition rate of 1 kHz. We tested 1 m and 3 m long stretched flexible fibers with 250/360 μm and 320/440 μm inner/outer diameters both filled with argon. The beam was focused into the fibers by a single thin fused silica lens with a focal length of 750 mm (for 250 μm ID) or 1000 mm (for 320 μm ID), respectively. In both cases the focal spot sizes were slightly larger than optimal (~70% instead of 64.4% of the ID).

The beam profile behind the evacuated fibers was always circular with a strong central core (containing 97% of the full transmitted energy) and a low intensity ring system around it. The transmission of the evacuated fibers related to the central core is shown in Table 1.

In all cases the measured transmission was about 80% of the corresponding theoretical value independent of the actual fiber. The discrepancy is attributed to beam launching losses due to the nonperfect laser beam quality. Furthermore, propagation of the energetic beam through the focusing lens induces a B-integral of ~1 which is already manifested in the spectrum through SPM and enhances the phase distortions originally present in the beam through self-focusing.

The spectrum of the pulses emerging from the hollow fiber unit was characterized by an Ocean Optics HR4000 spectrograph whose spectral response was corrected by measuring a calibrated halogen light source (Mikropack HL-2000). The beam was focused through a diffuser plate onto the entrance of a fiber connected to the spectrograph, in order to sample all spectral components correctly from the whole beam profile. A homemade single-shot imaging spectrograph was also used to check the spatial distribution of the spectrum along the beam profile 120 cm behind the fiber exit. The imaging spectrograph had higher spectral sensitivity at shorter wavelengths, which was not corrected.

Figure 1 shows similar spectral broadening achieved by a 1 m fiber of 250 μm ID filled with Ar at a constant pressure of 300 mbar and by a 3 m fiber of 320 μm ID filled with 200 mbar Ar. In the first case a transmission of 42% was achieved at a 9.2 times broadening of the root-mean-square (RMS) bandwidth. In the latter case the measured transmission to the central core of the output beam was as high as 64% at a slightly larger broadening factor of 9.7.

Table 1. Transmission of the Tested Hollow Fibers

L [m]	ID [μm]	Tmeas	Tth	Tmeas/Tth
1	250	69.1%	85.7%	80.6%
1	320	76.7%	92.0%	83.4%
3	250	53.6%	65.5%	81.9%
3	320	66.5%	80.9%	82.2%

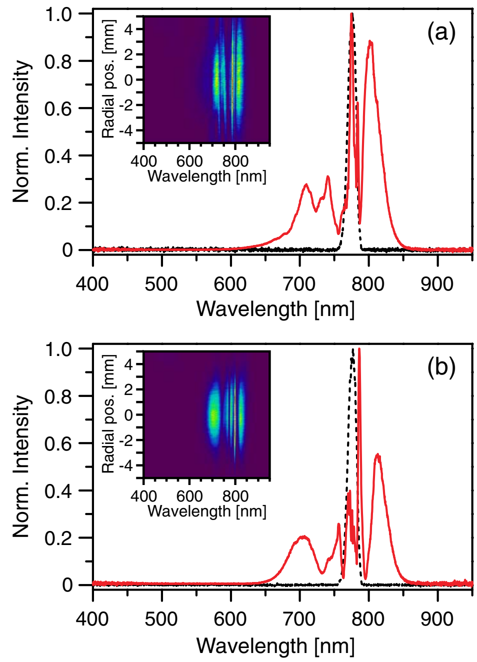

Fig. 1. (Color online) Similar spectral broadening achieved in (a) 1 m fiber of 250 μm ID filled with 300 mbar Ar and in (b) 3 m fiber of 320 μm ID filled by 200 mbar Ar. The input spectrum is shown by dashed black line. The inlets show the spectral distribution along the lateral position of the beam profile recorded by the imaging spectrograph.

The more than 50% higher transmission of the long fiber confirms the conclusion of (3).

The ultimate spectral broadening with still regular spectral shape and acceptable spatial homogeneity achieved by 1 m and 3 m fibers are shown in Fig. 2. A 15 times broadening of the RMS bandwidth was achieved at a transmission of 36% by using a 1 m long capillary of 250 μm ID with 500 mbar argon fill. A significantly larger broadening factor of 26 was achieved at a transmission level of 48% with a 3 m long 320 μm ID fiber filled with argon at 500 mbar pressure. In both cases, further increasing the gas pressure results in a rapid drop of the transmission, furthermore the spectrum becomes more irregular and inhomogeneous without significant broadening. Numerical calculations confirmed that the asymmetry in spectral broadening displayed in Fig. 2 is exclusively caused by self-steepening.

The spectrally broadened pulses shown in Fig. 2(b) were compressed by altogether 12 reflections on ultrabroadband chirped mirrors supporting 1.5 octave bandwidth having a group delay dispersion (GDD) of $-20\,\mathrm{fs}^2$ [15]. The fine optimization of the chirp compensation was achieved by propagating the pulses through a variable delay line in air. The pulses were characterized by a multiple-shot, all-reflective second-harmonic generation FROG device incorporating a 12 μm thick beta barium borate (BBO) crystal (cut at 30.8°) as nonlinear medium. The measured FROG trace (grid size: 512, error: 0.60%) is shown in Fig. 3.

The compressed pulses of 4.5 fs exhibit large pedestals (the central peak contains 58% of the pulse energy) and their duration is larger than the transform limit of 3.2 fs [red line in Fig. 3(d)]. This indicates that the available

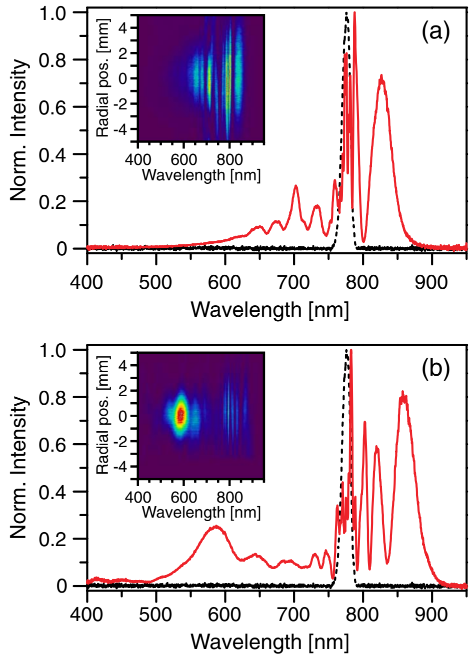

Fig. 2. (Color online) Broadest regular spectra achieved by (a) 1 m fiber of 250 μm ID and (b) 3 m fiber of 320 μm ID, both are filled with Ar at a constant pressure of 500 mbar.

chirped mirrors did not provide proper high-order chirp compensation. By applying mirrors with optimized chirp compensation it should be possible to compress the pulses to sub-4 fs duration. The lower intensity of the IR part of the spectrum in Fig. 3(c) compared to that of Fig. 2(b) is due to the shape of the reflectivity curve of the chirped mirrors [15], which also reduced the compressed pulse energy to 0.42 mJ.

As a conclusion, we demonstrated that a 3 m long stretched capillary clearly outperforms the standard 1 m long hollow fibers in terms of both the achievable compression ratio and the transmission. Starting from transform limited pulses of 71 fs we could generate 4.5 fs pulses with high transmission in a single compression stage. The achieved broadening factor of the RMS bandwidth is 26 and the ratio between the transform limited durations (FWHM) corresponding to the output and input spectra is 22, which are to our knowledge the highest values ever achieved by using a hollow fiber. The stretched flexible hollow fiber technology enables free length scalability keeping the waveguide properties optimal. Moreover, its construction inherently supports the pressure gradient scheme. Therefore, we believe the stretched flexible capillaries can give new impetus to the hollow fiber compression technique and paves the way towards even shorter pulse durations and higher pulse energies.

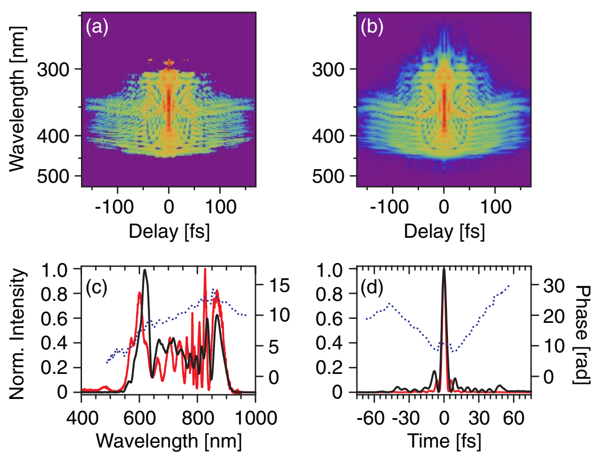

Fig. 3. (Color online) SHG FROG measurement of the compressed 4.5 fs pulse. The (a) measured and (b) retrieved FROG traces (with logarithmic color map), the retrieved (c) spectral and (d) temporal profiles are shown. The red curve in (c) displays the spectrum recorded by an external spectrometer, in (d) the transform limited pulse shape.

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