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# High-energy ultrashort laser pulse compression in hollow planar waveguides

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We demonstrate compression of high energy ultrashort laser pulses by nonlinear propagation inside gas-filled planar hollow waveguides. We adjust the input beam size along the non-guiding dimension of the planar waveguide to restrain the intensity below photoionization, while the relatively long range guided propagation yields significant self-phase modulation (SPM) and spectral broadening. We compare the compression in different noble gases and obtain 13.6 fs duration with output pulse energy of 8.1 millijoule (mJ) in argon, and 11.5 fs duration with 7.6 mJ energy in krypton. The broadened spectra at the output of the waveguide are uniform over more than 70% of the total pulse energy. Shorter duration could be obtained at the expense of introduction of spatial structure in the beam (and eventual formation of filaments) resulting from small-scale self focusing in the non-guided direction.

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The advent of high energy laser pulses with durations of few optical cycles provided scientists with very high electric fields, sufficient to suppress the Coulomb potential in atoms, accelerate electrons up to keV energies and produce coherent intense UV and XUV radiation with durations of attoseconds [1, 2]. Ultrashort-pulsed laser amplifiers can easily provide pulse energies in mJ and even joule levels, but with pulse durations longer than 20 fs. Amplification of pulses with shorter durations even to the mJ level is a difficult task requiring elaborate setups [3]. Durations down to the few-cycle regime can be achieved through pulse compression schemes such as gas-filled hollow core fibers [4] and filamentation [5]. Ionization and damage to the fiber limit the output energy of the hollow fiber scheme to sub-mJ levels, which can be extended to few-mJ using pressure gradients [6]. Due to multiple filamentation and intensity clamping, filamentation also yields sub-mJ energies. It was proposed recently that planar hollow waveguides can allow generation of few cycle pulses with much higher energies [7]. In the first experimental demonstration of this principle Chen et al. generated pulses of 12 fs duration with 2 mJ energy [8].

In this work we show that the concept of pulse compression in gas-filled planar hollow waveguides can actually support much higher pulse energies. In particular, we experimentally obtain pulses of 11.5 fs duration with energies of up to 7.6 mJ, without compromising the output beam quality. We compare the performance of the scheme using argon, krypton and xenon as nonlinear media. We show that the beam breakup into filaments can be avoided by adjustment of the gas pressure. The spectral broadening is spatially uniform over more than 70% of the total energy.

As for hollow core fibers, planar dielectric hollow waveguides support only leaky modes [9], the losses becoming sufficiently low only when the waveguide separation is much larger than the wavelength of the guided radiation. One particular advantage of planar waveguides as

compared to hollow core fibers is that the beam is guided in only one transverse direction, hence the guided intensity can be controlled by adjusting the beam size in the other direction, thereby allowing higher total energies [7]. Here we consider the beam propagating in  $z$  and guided in  $x$  direction while having a free-space diffraction (e.g. with Gaussian profile) in the  $y$ -dimension. Hollow planar waveguides support TE and TM modes in the form of [9]:

$$E(x, y, z) \propto E(y) \sin\left(\frac{m\pi x}{2a} + \varphi_x\right) \exp(-i\beta z) \quad (1)$$

where  $2a$  is the waveguide separation,  $\varphi_x$  is the parity ( $\varphi_x = 0$  for  $m$  even and  $\varphi_x = \pi/2$  for  $m$  odd) and  $\beta$  is the complex propagation constant, the real part of which determines dispersion while the imaginary part determines the losses:

$$\text{Re}(\beta) = \frac{2\pi}{\lambda} \left[ 1 - \frac{1}{2} \left( \frac{\lambda m}{4a} \right)^2 \right] \quad \& \quad \text{Im}(\beta) = -\frac{1}{a} \left( \frac{m\lambda}{4a} \right)^2 \left[ \frac{1}{(n^2 - 1)^{1/2}} \right] \quad (2)$$

for TE modes ( $\text{Im}(\beta)$  is multiplied by  $n^2$  for TM), where  $\lambda$  is the wavelength and  $n$  is the index of refraction of the glass. When  $a$  is sufficiently large, high throughputs are possible in the fundamental mode. The higher order modes will be reduced by lower coupling efficiencies and higher losses. For example, with a separation of 127  $\mu\text{m}$  and input beam radius of 50  $\mu\text{m}$ , 98% of the energy is coupled to the fundamental mode ( $m=1$ ) and  $<1\%$  to the first non-zero-coupling higher order mode the ( $m=3$ ). After 20 cm propagation, the losses are 5.8 % for  $m=1$  and 41 % for  $m=3$ .

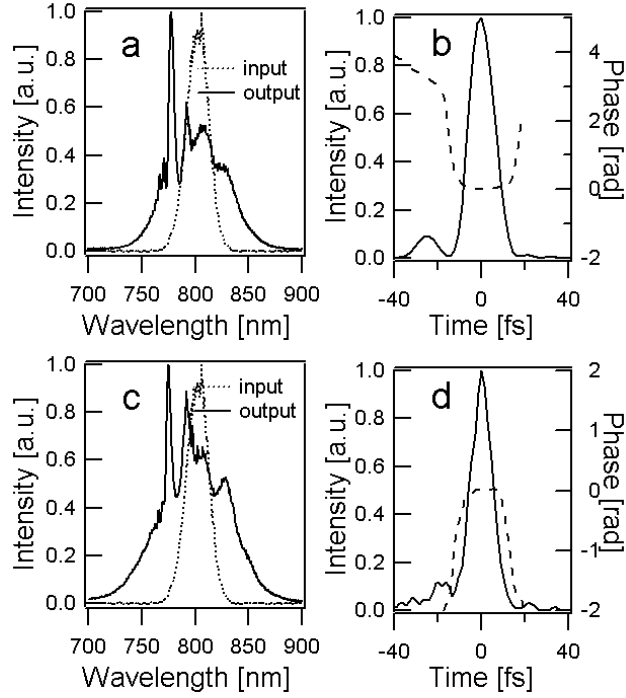


Fig.1 The input and output spectra and measured temporal intensity and phase for pulses compressed in a planar hollow waveguide filled with argon at 1.5 atm (a-b) and krypton at 1 atm (c-d). The compressed durations are 13.6 fs and 11.5 fs, respectively.

In our experiments, we used a Ti:Sapphire CPA system delivering 15 mJ pulse energy at 100 Hz with 45 fs duration. The beam  $1/e^2$  radius is 6.8 mm and polarization is along y (TE). We constructed a planar waveguide using two fused silica slabs (21 cm long, 1.9 cm wide and 0.6 cm thick) separated by 127  $\mu\text{m}$  thick plastic spacers. The waveguide is kept in a 2 m long gas cell with anti-reflection coated input and output windows (1 mm thickness fused silica). We fill the gas cell with different noble gases (argon, krypton and xenon) at adjustable pressures. We couple the laser beam into the waveguide using 1.3 m focal length cylindrical mirror (focused beam width is  $\sim 50\mu\text{m}$  along  $x$ ). The intensity in the waveguide is at the level of  $10^{13}\text{W}/\text{cm}^2$ , causing minor photoionization ( $\sim 10^{15}\text{cm}^{-3}$  electrons in argon). At the output of the cell we collimate the beam using another 1.3 m focal length cylindrical mirror. We measure the pulse spectrum using a fiber-coupled spectrometer (Ocean Optics HR4000). We compensate the spectral phase using a set of chirped mirrors with total group delay dispersion of  $\sim -300\text{fs}^2$  and third order dispersion of  $\sim -290\text{fs}^3$ . We measure the compressed intensity and phase of the pulse using a single-shot FROG capable of measuring pulses down to the single cycle regime [10].

Figure 1 shows our experimental results of pulse compression using the planar waveguide (measured at the center of the beam). The upper row (Fig.1a-b) shows the input/output spectra and measured intensity and phase obtained using argon (1.5 atm) and Fig.1c-d shows the same measurements obtained using krypton (1 atm). The pulse energy at the entrance of the cell is 12.5 mJ. In both cases, significant spectral broadening is apparent. After the phase compensation, the measured pulse duration and the total energy at the output are 13.6 fs (FWHM) and 8.1 mJ in the case of argon; 11.5 fs and 7.6 mJ for krypton. We also performed similar experiments in xenon (1 atm) and obtained  $\sim 11$  fs pulses whereas the maximum output energy before beam filamentation was limited to 3.7 mJ. The throughputs are lower compared to the value calculated above due to clipping of beam wings by the spacers and finite photoionization. To our knowledge, these measurements constitute the first experimental demonstration of pulse compression with such high output energies obtained through self-phase modulation (higher pulse energies with similar durations can be obtained through optical parametric chirped pulse amplification [3], but with significant increase in experimental complexity).

The beam quality after compression is a crucial consideration, as the spatial structure limits focusability. Small-scale self focusing causes the amplification of noise in the beam and deterioration of the spatial mode. At sufficiently high input energy the beam can even break into filaments [8]. For nonlinear propagation in a planar waveguide, since any mode other than the fundamental in the guided direction is strongly attenuated, one expects small scale self focusing to act only in the free direction. We recorded the output spatial profiles after the gas cell by projecting the beam on a white screen and imaging it to a CCD camera (UEye 2210M). Some of the measured beam profiles are shown in Fig.2 (horizontal is the free direction). For Fig.2a, the input pulse energy is kept low (in the linear propagation regime) and the beam exhibits a smooth quasi-single-mode profile. Profiles in Fig.2b-c correspond to the compression results mentioned above for argon at 1.5 atm and krypton at 1 atm respectively (see Fig.1), with input energy of 12.5 mJ. The beam quality is still preserved, apart from the appearance of minor structure, only in the free direction as expected. On the other hand, when we increased the pressure of krypton to 1.3 atm, the beam becomes highly modulated and we observe filaments being formed sporadically (Fig.2d).

The focusability is also affected by spatial phase distortions. Along the  $y$  direction, the nonlinear refractive index gives rise to wave-front retardation with the shape of the transverse intensity profile. We measured the focused intensity profiles directly on the CCD behind a 1 m focal length lens. We compared the focusability of beams at the output of the laser, after the

waveguide in the linear regime ( $\mu\text{J}$  energy) and after the waveguide in the nonlinear regime (with parameters of Fig.2b). Figure 2.e shows the focused beam profile after the waveguide in the linear regime, which closely matches that of the beam directly after the laser. On the other hand, in the nonlinear regime, the wave-front retardation causes astigmatism (see fig.2f) and yields a larger waist in the  $y$  direction and hence less intensity (corresponding to a Strehl ratio of 53%). To improve the intensity and focused beam quality, the wave-front can be compensated using adaptive optics [11].

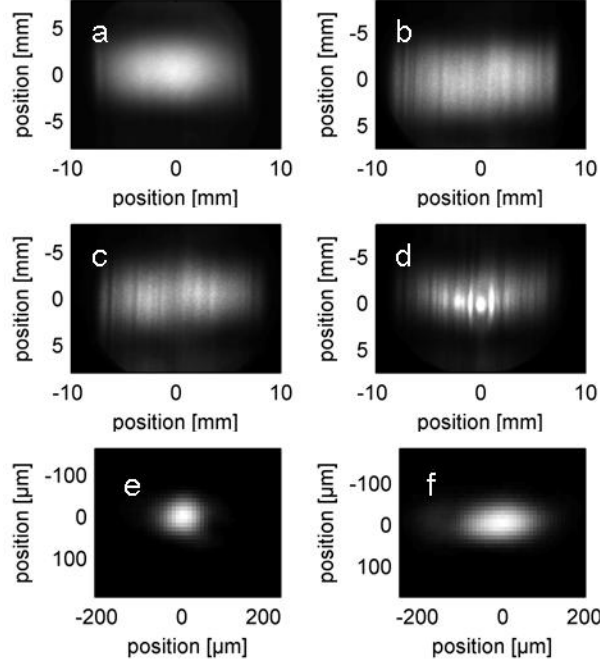


Fig. 2 Output spatial beam profiles of beams after propagation through the planar waveguide: in linear (a) and nonlinear propagation regime with 12.5 mJ input energy in 1.5 atm argon (b), 1 atm krypton (c) and 1.3 atm krypton (d). Focused beam profiles in the linear (e) and nonlinear (f) regimes.

The uniformity of the spectral broadening and hence pulse compression over the beam profile should also be considered. Since the intensity is of Gaussian shape in the  $y$  direction, the spectral broadening and compressed pulse duration is  $y$ -dependent. (as simulated in [7]). We measured the output spectra behind a narrow pinhole placed at different positions in the beam. For these measurements we used argon at 1 atm, with input pulse energy of 12.7 mJ. Total output energy was 9 mJ. Figure 3 shows the spectra at different  $y$ -positions, as well as the total pulse energy contained within an aperture with radius of the measurement points. The output spectrum is uniform for over a distance of more than 4 mm from the center, what contains  $\sim 73\%$  of the total energy. Beyond this position the spectrum starts to become somewhat narrower.

Lastly, in the planar waveguide compression scheme, the spectral structure resulting from SPM and non-compensated higher order phase causes pre-pulses (see Fig.1) and reduces the short-time temporal contrast [12], while the nanosecond-scale contrast (resulting from ASE) should be preserved. For application requiring high temporal contrast, the femtosecond pre-pulses can be cleaned using additional contrast improvement schemes [13].

In conclusion, by using gas filled hollow planar waveguides, we compress 10 mJ level energy ultrashort laser pulses. We experimentally demonstrate compression from 44 fs to 11.5 fs with total output energy of 7.6 mJ, without beam breakup into individual filaments. The

broadened output spectrum is uniform over more than 70% of the total energy. These results provide a significant improvement in extending pulse compression methods to high energies. [7].

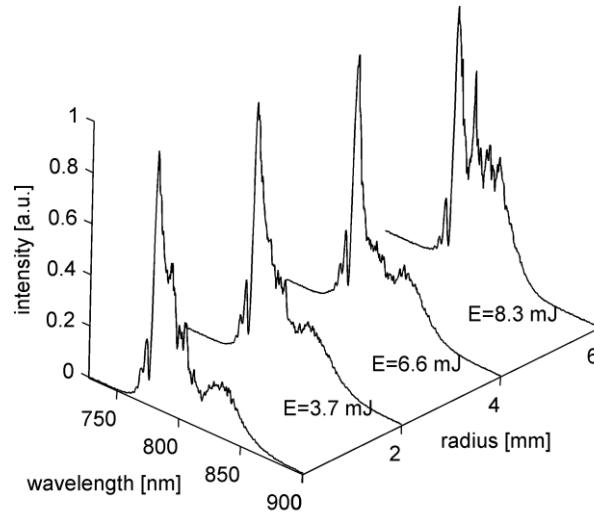


Fig. 3 Spectra measured behind 1 mm pinhole placed at different positions along the non-guided axis of the beam (the position  $0$  is the beam center). The pulse energies contained within the radii are also indicated.

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