Compression of ultrashort laser pulses in planar hollow waveguides: a stability analysis

C.L. Arnold¹, S. Akturk², M. Franco¹, A. Couairon³ and A. Mysyrowicz¹

¹Laboratoire d’Optique Appliquée, École Nationale Supérieure des Techniques Avancées - École Polytechnique, CNRS, F-91761 Palaiseau, France
²Department of Physics, Istanbul Technical University, Maslak 34469 Istanbul, Turkey
³Centre de Physique Théorique, École Polytechnique, CNRS, F-91128 Palaiseau, France
cord.arnold@ensta.fr

Abstract: We investigate compression of ultrashort laser pulses by nonlinear propagation in gas-filled planar hollow waveguides, using (3+1)-dimensional numerical simulations. In this geometry, the laser beam is guided with a fixed size in one transverse dimension, generating significant spectral broadening, while it propagates freely in the other, allowing for energy up-scalability. In this respect the concept outperforms compression techniques based on hollow core fibers or filamentation. Small-scale self-focusing is a crucial consideration, which introduces mode deterioration and finally break-up in multiple filaments. The simulation results, which match well with initial experiments, provide important guidelines for scaling the few-cycle pulse generation to higher energies. Pulse compression down to few-cycle duration with energies up to 100 mJ levels should be possible.

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References and links

1. Introduction

One of the main goals of today’s ultrafast nonlinear optics is the compression of ultrashort laser pulses down to the few-cycle regime. Intense few-cycle infrared (IR) laser pulses with reproducible carrier envelope offset are key ingredients in attosecond physics, serving both as driving pulses for the generation of intense coherent sources in the extreme ultraviolet (XUV) wavelengths [1] and as short intense streaking pulses in the near infrared [2, 3]. Near single-cycle pulses are commonly generated through nonlinear propagation in gas-filled hollow fibers [4] or through optical filamentation in noble gases [5, 6, 7, 8]. Due to potential damage to the fiber, the hollow fiber scheme supports pulse energies typically limited to sub-millijoules, in particular when driven at kHz-repetition rates. At low repetition rate and by using a pressure gradient along the fiber the output was recently increased to some millijoules of pulse energy [9]. Pulse compression through filamentation is limited to the same energy levels, caused by intensity clamping, inherent chirp and angular dispersion within the filament [10, 11, 12] or by the onset of multiple filaments. To date, few-cycle pulses with higher energies (up to ~100 mJ) are mainly generated through optical parametric chirped pulse amplification (OPCPA) [13, 14]. These setups involve considerable experimental complexity and require the use of additional pump lasers.

Recently, the theoretical work of Nurhuda et al. [15] suggested a compression scheme using gas-filled planar hollow waveguides, which can address the issue of energy upscalability with significantly less experimental complexity. As the beam is guided in only one transverse direction (short axis), the perpendicular direction (long axis) can be utilized to freely adjust the beam size and intensity with the objective of limiting photo ionization on the one hand, and achieving strong self-phase modulation (SPM) and spectral broadening, essential to reach the few-cycle
regime, on the other hand. While the simulation results presented by Nurhuda et al. [15] are promising, the initial experiments by Chen et al. and Akturk et al. showed that the transverse spatial propagation dynamics imposes severe restrictions on the energy up-scalability [16, 17]. Imperfections and noise in the input spatial mode are amplified by small-scale self-focusing, resulting in output beams with complicated spatial structure and multiple filaments. Nonetheless, the planar waveguide scheme holds its promise for high energy pulse compression, but a better understanding and more practical and complete analysis of nonlinear pulse propagation inside the waveguide is needed.

In this work, we present a comprehensive analysis of nonlinear propagation and pulse compression via planar hollow waveguides. In practice a planar hollow waveguide can be composed of two polished glass surfaces facing each other and separated by thin spacers. It should be noted that this structure strictly speaking is not a planar waveguide, since the modes are lossy. However, the losses are small for the thickness of the spacers considered. For simplicity we keep the term waveguide throughout the paper. We present the results of detailed (3+1)-dimensional simulations of the spatio-temporal pulse dynamics in the waveguide, which provides understanding of the energy and compressibility limits of this technique, from which a practical criterion to reach the best pulse compression without compromising the spatial mode is established. Careful validation of our modeling is achieved by comparing simulated compressed pulse temporal shape and spatial mode with experimental results [17]. The model is then applied to define the conditions for the compression of very energetic pulses (>100mJ) down to the few-cycle regime (<10fs) as well as for the possible compression of few-cycle pulses with more than 15mJ energy to the single-cycle regime.

2. Numerical simulation results and experimental comparison

Nonlinear propagation inside the gas-filled planar hollow waveguide is modeled by the Nonlinear Envelope Equation (NEE) [18], known to be valid to the single-cycle regime [19]. The description of the interaction of the ultrashort pulse with the argon gas inside the waveguide comprises a Kerr-type nonlinearity for self-focusing and self-phase modulation (nonlinear index of refraction \( \tilde{n}_2 = n_2/P = 0.98 \times 10^{-19} \text{cm}^2\text{W}^{-1}\text{bar}^{-1} \) [20]), plasma generation via optical field ionization with rates calculated from the generalized Keldysh-PPT formula [18, 21], plasma defocusing, as well as higher order dispersion, self-steepening, and space-time focusing. The NEE is numerically integrated in a split-step method, treating the nonlinear part via the field dependent nonlinear polarization and the linear part in mode space, allowing us to properly describe exact coupling between high-order modes, dispersion and losses induced by the waveguide as well as guided propagation along the short waveguide axis and free propagation in the perpendicular transverse direction. For this purpose, the electric field is decomposed into a basis of leaky transverse electric (TE) waveguide even modes \( V_{p=2m} (x) = \sin (p \pi x/2a) \) and odd modes \( V_{p=2m-1} (x) = \cos (p \pi x/2a) \). The transformation from one representation to the other reads:

\[
E(x,y,t,z) = \sum_p V_p(x) A_p(y,t,z) e^{i(\beta_p z - \omega_p t)}
\]

\[
A_p(y,t,z) = \frac{1}{a} \int_{-a}^{a} V_p(x) E(x,y,t,z) dx
\]

where \( E \) is the complex envelope of the field and \( A_p \) of the leaky mode with index \( p \); \( 2a = 127 \mu \text{m} \) is the separation of the glass slabs (refractive index \( n = 1.45 \)) constituting the waveguide. The dependence upon frequency of propagation and attenuation constants \( \beta_p(\omega) = k(1-(p\pi/2ka)^2)^{1/2} \) with \( \beta_{p,0} = \beta_p(\omega_0) \) and \( \alpha_p(\omega) = p^2 \pi^2/(4k^2a^2) \sqrt{n^2 - 1} \) is obtained from the wave number \( k(\omega) \) calculated from the dispersion data of argon [22], which
Fig. 1. Normalized power propagating in the waveguide compared to the power of the fundamental mode. Relative powers of higher order modes are plotted below the break. Parameters are listed in Tab. 1.

also depends on pressure. In the linear part, the 2-dimensional Fourier transform $\tilde{A}_p(k_y, \omega, z)$ is propagated, thus no expansion around $\omega_0$ is made in the dispersion, absorption, and group velocity for each mode. Higher order modes decay much faster compared to the fundamental. Ten modes are sufficient to numerically propagate ultrashort pulses inside the waveguide.

The parameters for the calculations presented in Fig. 1 and 2 were chosen exactly as in the experiments of reference [17], namely a pulse duration of 43fs (FWHM), a beam size in the guided direction of $w_x = 0.7a$ close to the optimum coupling conditions, a beam size of $w_y = 7.2\, \text{mm}$ along the long waveguide axis, a pressure of argon of 1.5atm, and a waveguide length of 21cm (see also Tab. 1). Figure 1 shows the normalized power inside the waveguide compared to the power of the fundamental mode as well as higher order modes. Nonlinear coupling mainly occurs between the fundamental ($p = 1$) and the first excited mode ($p = 3$), whereas the length scale of the power oscillations corresponds to the beating length $L_b \approx 2\pi / (\beta_{1,0} - \beta_{3,0}) \sim 1\, \text{cm}$. Only a small portion of power is exchanged between higher order modes. In the simulations, the total throughput of the input energy is about 93% compared to 65% in the experiment. Different effects, which are not considered in the modeling, may cause this discrepancy, such as coupling losses due to inhomogeneities in the beam, imperfections of the waveguide, reflections from the windows of the gas cell, and beam clipping inside the cell. To better match the experimental conditions, the input pulse energy for the simulations was corrected for the additional loss; furthermore the measured input temporal intensity and phase was used. To mimic the experimental compression by negatively dispersive mirrors, the output pulse obtained from the simulations is compressed by applying second order phase delay only, leaving higher order chirp, picked up during nonlinear interaction, uncorrected. To also diagnose the output spatial mode quality, which is a crucial parameter for energy up-scalability, a measured beam profile with 4% intensity modulations compared to an ideal Gaussian profile was used as input along the long waveguide axis.

Figure 2 compares the experimental results of reference [17] with the modeling, showing convincing overall agreement. Note in particular that the total spectral and temporal widths coincide well in the spectrograms (2A,B), generated by means of frequency resolved optical gating (FROG) [10]. The phase of simulated broadened spectra (data not shown) features a strong second-order component, explaining the good compressibility with chirped mirrors. Fi-
Fig. 2. Comparison of the experimental results (left) and modeling (right). (A,B) Temporal profile of the output pulse after compression. (C,D) FROG trace. (E,F) Spatial profile at the output. Table 1 lists the parameters used in the simulations.

nally, also the transverse structure of the experimental output mode is numerically reproduced, provided a measured input beam profile is considered in the long transverse direction (2E,F). However, the depth of the transverse modulations is somewhat deeper experimentally. This could be due to additional imperfections of the beam and the waveguide, not accounted for in the simulations. Asymmetries in the guided direction are filtered by the waveguide (2E). The intensity of \( I_0 = 3.35 \times 10^{13} \text{ W cm}^{-2} \) keeps the density of generated free carriers well below \( 10^{15} \text{ cm}^{-3} \) (data not shown), minimizing propagation losses and limiting the nonlinear interaction to mainly self-phase modulation.

2.1. Analysis of the beam stability

The simulations clearly reveal that pulse compression in planar hollow waveguides is compromised by the deterioration of the output mode due to small-scale self-focusing (see Fig. 3, lower plot). To identify a regime of stable propagation, one must evaluate the length scales for instabilities to be avoided, namely \( L_{sf} \) for self-focusing of a beam of width \( w_y \) along the long transverse axis and \( L_{mi} \) for small-scale self-focusing (modulational instability) [23]. An analytical expression for \( L_{sf} \) (dashed line in Fig. 3) is obtained by deriving an evolution equation for the second order moment \( w^2(z) \equiv \int_{-\infty}^{\infty} y^2 |E|^2 dy / \int_{-\infty}^{\infty} |E|^2 dy \) [18]. Assuming whole beam Kerr self-focusing with a frozen beam profile, \( E \propto \exp(-y^2/w^2(z)) \), a direct integration between the entrance of the waveguide and the nonlinear focus can be performed which yields:

\[
L_{sf} = 2\pi z_{Ry} \left( \frac{P^*}{P_c} \right) \times \left[ 4 \left( \frac{P^*}{P_c} - 1 \right) \right]^{-3/2},
\]

where \( z_{Ry} \equiv k_0 w_y^2/2 \) is the Rayleigh length associated with \( w_y \), \( P^* = \pi \hbar^2 w_y^2/2 \) the power of a 2D beam with the same intensity and width and \( P_c = 2\pi n_0/k_0 n_2 \) is the critical power for 2D collapse. For \( P^*/P_c \gg 1 \) and constant intensity,
Fig. 3. Upper plot: Length of stable propagation versus the transverse beam size $w_y$ and pulse energy, with either a perfect input profile (triangles) or a measured input profile (circles) taken into account. The shaded area indicates the regime of stable propagation determined by the measured profile. The solid star marks the experimental conditions (ref. [17], Fig. 2), the open stars indicate the conditions used in Fig. 4. Lower plot: Modeled fluence along the waveguide for the experimental conditions.

$L_{sf}$ is roughly proportional to $w_y$. Small-scale self-focusing follows the theory of modulational instability [24] from which an evaluation of $L_{mi} \equiv \log(G)k_0P_c/2\pi I_0$ is found, where $G$ denotes a gain that represents the amplification factor of small-scale inhomogeneities (both beam imperfections and generic noise) before saturation of the modulational instability in the form of filaments.

In Fig. 3 the upper plot shows the lengths after which either a nonlinear focus or beam break-up is numerically observed, as we scale the transverse beam size $w_y$ (long axis) and pulse energy, respectively at constant input intensity. Simulations with a perfect Gaussian transverse input beam profile along the long axis (indicated as triangles) greatly overestimate the distance of stable propagation as compared to simulations with a realistic (measured) profile used as an input condition (indicated as circles). The shaded area identifies the regime of stable propagation determined by the measured beam profile. For small $w_y$ the propagation distance is limited by self-focusing of either the whole beam or beam imperfections; for $w_y \gtrsim 20\text{mm}$ modulational instability defines the limit. The solid star corresponds to the experimental conditions of reference [17] and the simulations presented in Fig. 2, showing that the length of the waveguide (dotted line) was at the border of the permissible propagation distance. For these exact conditions the fluence along the waveguide is shown in the lower plot. Indeed, shortly after the length of the experimental waveguide (dotted line) the profile breaks into individual filaments, unsuitable for compression. Note that the length scales and the stability regime in Fig. 3 are valid...
Fig. 4. 2D (upper row) and 1D (lower row) temporal profiles of the compressed output pulse for the planar hollow waveguide scheme applied to very energetic pulses (left column) and pulses in the few-cycle regime (right column). Additional parameters are listed in Tab. 1.

for a particular combination of parameters only ($I_0 n_2 = \text{const}$). However, when modulational instability and not self-focusing determines the stability region, the distance of stable propagation can also be associated with a specific value of the B-integral $B \sim k_0 I_0 n_2 z$ (upper plot, solid line), where $z$ is the propagation distance. Its value $B \sim 15.5$ is solely determined by the amount of imperfections and noise contained in the measured input profile. This corresponds to a gain $G \sim 4.5 \times 10^4$. Experimentally, due to additional sources of noise, modulational instability may saturate below $B \sim 15.5$. For the parameters of reference [17] the B-integral corresponds to a value of $B \sim 8$.

2.2. Energy upscalability

Having defined the stability region for hollow planar waveguide pulse compression, we are now in a position to determine the waveguide and laser beam parameters, allowing to obtain higher pulse energies and shorter pulse durations. We particularly examine two cases: First, the compression of very energetic pulses ($>100\text{mJ}$) to durations of sub 10fs; and second, the compression of pulses, which already are in the few-cycle regime, to further advance to the single-cycle regime. The parameters are listed in Tab. 1. For the sake of simplicity we assume Gaussian spatial and temporal beam profiles and choose conditions, which can also be indicated in Fig. 3 (open stars). However, due to the different pulse durations only the length scale (lower axis) but not the energy scale (upper axis) is applicable. The compressed temporal output profiles for both cases are shown in Fig. 4. For the high energy pulse we calculate a compression from 40fs duration to below 10fs at 100mJ output energy (left column). The short pulse can be compressed from 10fs to below 3fs (almost a single-cycle pulse) at energy of 15.8mJ (right column), provided chirped mirrors of sufficient bandwidth (500 − 1200nm) are available. The 2D plots of the compressed pulse profiles (upper row) reveal a homogeneous compression close to the axis, whereas the pulse becomes longer towards the edge of the profile due to less self-phase modulation. For the case of the 100mJ pulse (Fig. 4, left column) about 70% of the pulse energy falls within a duration of 1.5 times the duration at the center. Simultaneously, the compressed pulse features a phase and pulse front delay in the center. Therefore, to achieve good...
focusability, the spatial phase has to be either pre or post compensated by, e.g. adaptive optics.

Table 1. Parameters used for the simulations in Fig. 1 and 2 and in Fig. 4 left and right

<table>
<thead>
<tr>
<th>Description</th>
<th>Fig. 1, Fig. 2</th>
<th>Fig. 4 left</th>
<th>Fig. 4 right</th>
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</thead>
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<tr>
<td>Input energy (mJ)</td>
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<td>107</td>
<td>16.7</td>
</tr>
<tr>
<td>Pulse duration (FWHM) (fs)</td>
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<td>40</td>
<td>10</td>
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<td>Waveguide half separation a (μm)</td>
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<td>63.5</td>
<td>63.5</td>
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<tr>
<td>Beam size guided direction w_x (μm)</td>
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<td>50.2</td>
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<td>Beam size free direction w_y (nm)</td>
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<td>95</td>
<td>40</td>
</tr>
<tr>
<td>Intensity at the input I_0 (Wcm⁻²)</td>
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<td>3.35 × 10¹³</td>
<td>5 × 10¹³</td>
</tr>
<tr>
<td>Argon pressure (atm)</td>
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<td>1</td>
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<tr>
<td>Length of the waveguide (cm)</td>
<td>21</td>
<td>21</td>
<td>16</td>
</tr>
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</table>

3. Conclusion

In conclusion, we have investigated the potential of planar hollow waveguides for the compression of ultrashort laser pulses in practical experimental conditions. Stability analysis revealed that the limit of possible compression is given by a B-integral threshold determined by the input spatial beam profile. Nonetheless, within the regime of stable propagation the scheme scales up to high energies and can as well be applied to advance from the few-cycle to the single-cycle regime. In this respect a two-stage compression seems feasible, with the additional benefit of also employing the waveguide in the second stage to filter spatial noise generated within the first stage.

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