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Guiding and high-harmonic generation of sub-10-fs pulses in hollow-core fibers at $10^{15}\,\mathrm{W/cm^2}$

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Abstract. Sub-10-fs laser pulses have been guided in the fundamental transverse mode of a hollow-core fused-silica fiber at intensities of $\approx (1-2) \times 10^{15}\,\mathrm{W/cm^2}$. The high resistance of fused silica to damage in the sub-10-fs regime allows stable reproducible operation without degradation of the capillary waveguide. In preliminary experiments, we demonstrate kHz-repetition-rate guided-wave high-harmonic generation in helium down to the 10-nm range. The reported experiments open up the way to realizing high-field interactions with plane-wave excitation at intensity levels in excess of $10^{15}\,\mathrm{W/cm^2}$ under well-controlled conditions.

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Recent advances in high-power ultrashort-pulse lasers have revived interest in the development of a compact, cost-effective, and versatile coherent XUV laboratory source. Ultrafast laser systems are now capable of providing high peak powers in combination with high average power, making them attractive candidates for compact drivers of XUV sources [1]. Efficient exploitation of this potential may rely on effective interaction lengths longer than the Rayleigh range of the focused laser beam, which is dictated by the required peak intensity and available peak power. This constraint can be relaxed by confining the laser beam in some suitable guiding structure.

Guiding (or channeling) of high-intensity laser beams over propagation lengths several times the Rayleigh range was previously implemented in plasma channels with nonrelativistic [2] and relativistic [3] laser intensities. Schemes using capillary discharges have also been proposed and exploited [4]. Confinement of intense laser beams in a solid-state structure (hollow-core fiber or microcapillary) [5] has also been demonstrated. The performance and practical utility of the latter scheme has been limited by optical breakdown in the waveguide material. The intensity threshold for optical breakdown is on the order of $10^{13}\,\mathrm{W/cm^2}$ for subpicosecond pulse durations. As a consequence, on-axis peak intensities exceeding $10^{14}\,\mathrm{W/cm^2}$ tend to give rise to a fairly rapid destruction of the waveguide unless the beam is focused to a spot size at the input port that is substantially smaller than the waveguide channel radius, which results in excitation of several higher-order transverse propagation modes [5].

In this paper, we demonstrate stable damage-free guiding of laser pulses in the *fundamental propagation mode* of a hollow-core waveguide [6] at the $10^{15}\,\mathrm{W/cm^2}$ intensity level for the first time. This progress has been enabled by (a) the availability of multigigawatt sub-10-fs laser pulses delivered in a diffraction-limited beam with a high pointing stability [7] and (b) the resistance of fused silica to intensities well in excess of $10^{14}\,\mathrm{W/cm^2}$ in the sub-10-fs regime [8]. Guiding of sub-10-fs pulses in the lowest-order waveguide mode at on-axis intensities of $10^{15}\,\mathrm{W/cm^2}$ has been achieved over a propagation length of about 8 times the Rayleigh length with a transmission efficiency of 50% in a well-controlled, reversible manner. Filling the waveguide with helium does not affect this throughput notably up to pressures as high as 100 mbar. These features make this scheme an attractive interaction geometry for both developing efficient coherent XUV sources and studying high-field phenomena (e.g. optical tunnel or above-barrier ionization) under well-controlled and well-defined conditions (uniform gas density distribution, absence of curved wavefronts, etc.).

The above laser pulse parameters are well suited for the generation of high-order harmonic radiation [9, 10]. High-harmonic generation has recently shown its potential to produce coherent short-wavelength radiation down to the water window [11, 12]. The high-harmonic yield has so far been limited by a phase velocity mismatch between the harmonic and laser radiation, which generally originates from plasma dispersion and the Gouy phase shift in a focused Gaussian beam [14]. The background-free electron density responsible for the former contribution can be substantially reduced by using sub-10-fs drivers, which increase the achievable high-harmonic production efficiency by more than two orders of magnitude as compared to 20-fs pump pulses [1]. The Gouy-shift-induced “geometric” mismatch, on the other hand, can be somewhat relaxed by waveguiding. As a matter of fact, by exploiting intense sub-10-fs propagation in a hollow-core waveguide, we demonstrate enhanced high-harmonic yield as compared to free-space propagation down to the 10-nm regime.

1 Experimental setup

The experiments have been conducted with a 0.1-TW Ti:sapphire laser system operating at a 1-kHz repetition rate and capable of generating pulses with 0.5 mJ of energy and a 5-fs pulse width [7]. The laser beam is focused with a $f = 200\,\text{mm}$ spherical mirror into a hollow-core fused silica tube with an inner diameter of $80\,\mu\text{m}$. The focal spot of about $60\,\mu\text{m}$ in diameter (beam waist $30\,\mu\text{m}$) is closely matched to the channel diameter to yield optimum coupling to the fundamental transverse propagation mode of the waveguide. The schematic of the setup is shown in Fig. 1. The He gas inlet is on the laser entrance side of the fiber. The other end of the capillary leads into an evacuated chamber, which can be used for possible manipulation and/or application of the coherent XUV radiation generated. Spectral characterization of the emitted short-wavelength radiation is performed by a 1-m grazing-incidence spectrograph equipped with a 300-l/mm platinum-coated grating. The transmitted signal is detected by an uncoated channeltron and a lock-in amplifier. Hence, the capillary also fulfills a second important function: it separates the gas-filled target chamber from the evacuated manipulation/detection chamber, resulting in a significant reduction in the gas load for the latter as compared to gas jet targets [11]. Future improvements of this configuration will include gas injection through a hole drilled in the capillary wall to avoid possible adverse effects of the gas nonlinearity on the pulse in front of the waveguide.

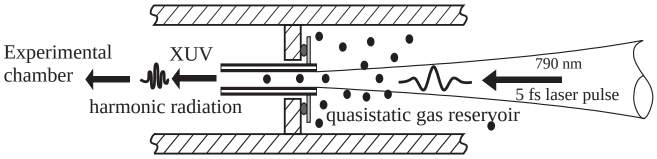

Fig. 1. Schematic of the experimental setup for guiding 5-fs pulses at on-axis intensity levels of $(1-2) \times 10^{15}\,\text{W/cm}^2$ in a hollow-core gas-filled fused-silica fiber. The inner diamater (ID) of the capillary waveguide is $80\,\mu\text{m}$. The fundamental propagation mode of the waveguide can be efficiently excited by setting the waist of the focused Gaussian beam equal to $\approx 30\,\mu\text{m}$ at the entrance to the waveguide

2 Guiding characteristics

The experiments described in this section have been performed with a 20-mm-long waveguide. Figure 2 shows the intensity profile of the sub-10-fs laser beam entering and exiting the capillary with an on-axis intensity of $10^{15}\,\text{W/cm}^2$ at the exit port of the capillary. This measurement provides clear evidence for guiding being achieved in the fundamental waveguide mode. Once alignment is completed (which is performed with the beam attenuated) the experiment can run stably over hours due to the excellent beam pointing stability of the laser system. Although repeated alignment and operation over extended periods of time may result in some front-surface damage that can be recognized under a microscope, this does not lead to a significant degradation of the quality of the transmitted mode and the capillary throughput. This latter can be reproducibly kept in the range of 40%–50%. The relative transmittivity of the capillary with gas filling is shown in Fig. 3 for two different noble gases (argon and helium) as a function of the pressure. Generally, increasing the gas density enhances not only absorption but also energy coupling to higher-order transverse modes via ionization. The latter effect also reduces the throughput due to increased proapagation losses of the higher-order modes and, in addition, impaires the output beam quality. In argon, which has an ionization potential of $I_\text{p} = 15.76\,\text{eV}$, these effects become significant at pressures higher than 10 mbar. Self-defocusing of the incident beam in front of the waveguide entrance may also reduce the transmittivity. In strong contrast, helium allows nearly loss-free spatially undistorted propagation up to pressures as high as 100 mbar (owing to its high ionization potential of 24.59 eV) even at these high intensity levels. These results show that for helium our simple setup works well up to a pressure of 100 mbar, which may be sufficient for efficient harmonic production (see below). In regard to the temporal evolution of the pulse propagating down the waveguide, our simulations have shown that only insignificant temporal broadening of a 5-fs pulse is expected for a propagation length of 5 mm at an assumed constant pressure of 10 mbar and a peak intensity of $10^{15}\,\text{W/cm}^2$ in helium. Increasing the

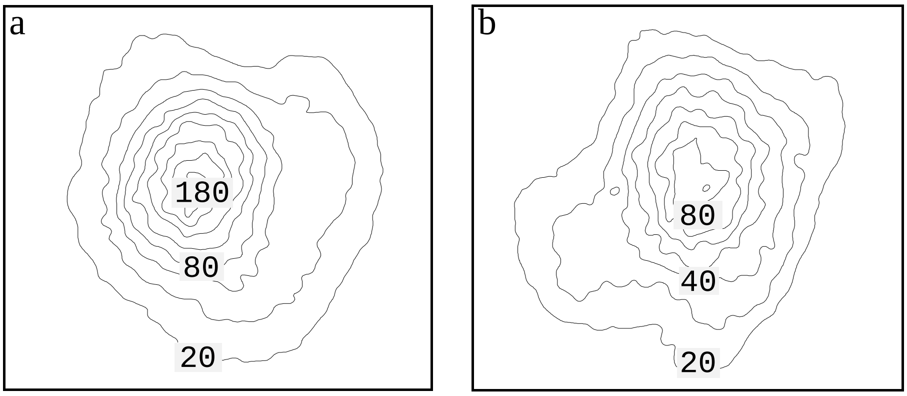

Fig. 2a,b. Input (**a**) and output (**b**) beam profiles for a 5-fs laser pulse channeling through a 2-cm-long hollow-core fiber (ID $= 80\,\mu\text{m}$ diameter) at an on-axis peak intensity of about $10^{15}\,\text{W/cm}^2$ (at the waveguide exit). The transmission efficiency is $\approx 50\%$

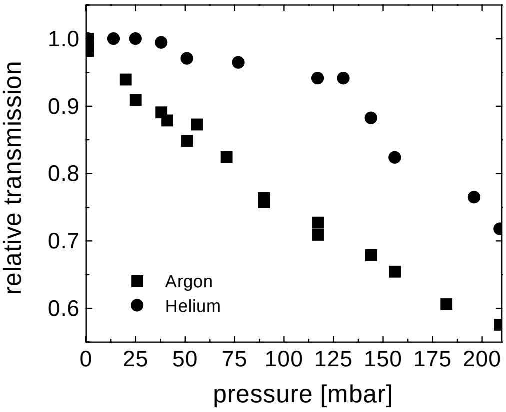

Fig. 3. Relative pulse energy transmitted by a 2-cm-long capillary (ID = 80 μm) filled either with He (*circles*) or with Ar (*squares*) as a function of gas pressure p for 5-fs pulse duration and a peak on-axis intensity of $\approx 10^{15}\,\mathrm{W/cm^2}$ at the waveguide exit. The absolute transmission efficiency for $p = 0$ is 50%

pressure to 25 mbar and 100 mbar, however, introduces pulse broadening by a factor of ≈ 1.6 and ≈ 2, respectively.

3 High-order harmonic production

The preliminary high-harmonic generation experiments have been performed using 5-mm-long capillaries filled with He. In a first series of experiments the gas pressure was varied in the range of 10–100 mbar, in which no significant transmission losses are observed. The XUV signal originating from the microcapillary as a function of the pressure at wavelengths of 10, 20, and 30 nm is depicted in Fig. 4. Qualitatively, the XUV signal is expected to increase with increasing pressure until the plasma-dispersion-limited coherence length L_p becomes as short as the coherence length L_wg limited by waveguide dispersion. This latter is calculated as $L_\mathrm{wg} \approx 170\,\mu\mathrm{m}$ (for a dephasing of π) for 10-nm radiation and is inversely proportional to the wavelength of harmonic radiation. However, at the lowest intensities where the investigated XUV wavelengths appear on the leading edge, the ionization grades are on the order of 1% for sub-10-fs pulses, which implies significantly larger values for L_p at a pressure of 15 mbar than obtained for L_wg. Beyond this phenomenon, the observed monotonous decrease of the XUV signal for increasing pressure at $p > 15$ mbar is also not well understood. Plasma-induced pulse broadening in the capillary and defocusing in front of the fiber entrance are possible candidates to account for the observed behavior. The first effect remains less than a factor of 2 even for the highest pressures applied and hence does not appear to be the responsible effect. The second effect apparently cannot account for the observed behavior either, because the transmittivity scarcely changes over the relevant pressure range, as shown in Fig. 3. Yet, an accumulating nonlinear phase shift in front of the capillary might lead to energy coupling into higher-order Gauss–Hermite propagation modes of free space, giving rise to excitation of higher-order waveguide propagation modes and thereby impairing high-harmonic production. In order to look at this problem experimentally, a more advanced setup with gas injection through a hole drilled in the capillary wall in the middle of the fiber and pumping at both fiber ends will have to be used to avoid pulse propagation in the gas reservoir.

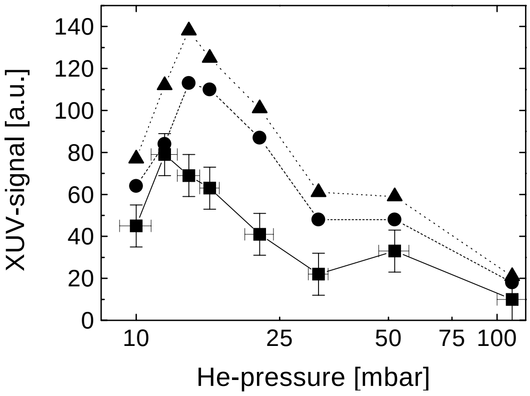

Fig. 4. Coherent XUV harmonic signal (*squares* $\lambda = 10$ nm, *circles* 20 nm, *triangles* 30 nm) emerging from a 5-mm-long capillary with ID = 80 μm filled with He as a function of pressure for 5-fs pulses launched with an on-axis peak intensity of $\approx 2 \times 10^{15}\,\mathrm{W/cm^2}$ into the waveguide

To gain some information about the role of guiding in the high-harmonic-generation process the 80 μm capillary was replaced with another one having an inner diameter of 250 μm without changing anything else in the experimental setup. Inspection of the relevant equations describing gas flow and density distribution along the capillary yields that, in spite of the strongly different gas throughput, the longitudinal density gradient in the capillary is approximately the same in both cases. Hence, the only essential difference in the experimental conditions relates to laser-beam propagation; guiding in the 80-μm fiber can be contrasted with free-space propagation in the 250-μm fiber. Figure 5 compares the high harmonic spectra obtained under guided and nonguided conditions, using the same pulse parameters and focussing geometry. The discrete harmonic structure at long wavelengths merges into a continuum at the short-wavelength end of the spectrum as a direct consequence of the quasi-single-cycle nature of the laser pulse [1]. Maximum XUV yield is observed at pressures of $p_\mathrm{opt} \approx 13$–15 mbar and the XUV output decreases for higher pressures in both cases. Differences in the behavior of the two propagation geometries include the significantly higher (factor of 5–6) signal levels and somewhat slower decrease of the XUV output with increasing pressure under guiding conditions.

In an attempt to gain some insight into the origin of the different behavior of the two systems, we have contrasted the waveguide-dispersion-limited coherence length of $L_\mathrm{wg} \approx 170\,\mu\mathrm{m}$ with the corresponding Gouy-shift-limited co-

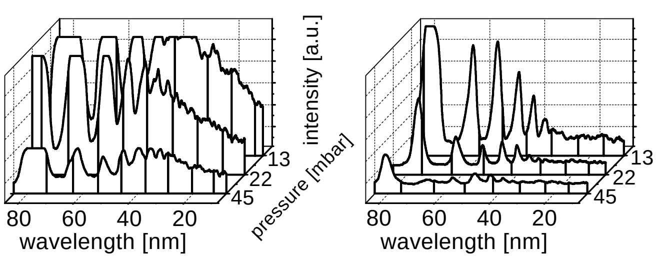

Fig. 5a,b. XUV harmonic spectrum generated at different pressures under guiding(**a**) and nonguiding (**b**) conditions. For explanations see the text herence length, which is evaluated as $L_{\mathrm{Gouy}} \approx 140\,\mu\mathrm{m}$. From $L_{\mathrm{Gouy}} < L_{\mathrm{wg}}$ it follows that the p_{opt} yielding the maximum XUV output should shift to higher values for the nonguided geometry than for waveguiding if plasma dispersion constituted the dominant effect limiting the XUV yield. Also, if this assumption applied, the maximum XUV yield, though realized at different values of p_{opt}, should be comparable for both geometries. Since neither of these expectations is met, we conclude, in accordance with the above findings, that *plasma dispersion does not appear to be a limitation under our experimental conditions*. We surmise that energy coupling from the fundamental into higher-order propagation modes might be responsible for the observed behavior. This hypothesis is supported by recent theoretical investigations of this issue and related self-focusing or self-defocusing effects (depending on the type of nonlinearity), which indicate that a larger phase velocity mismatch stops the accumulation of energy transferred into higher-order modes at significantly lower levels in a hollow-core waveguide as compared to corresponding free-space propagation [15]. The enhanced energy transfer into higher-order modes might interfere more strongly with high-harmonic production in the nonguiding geometry. Direct comparison of the coherent XUV output from the above interaction geometries with that originating from a free-streaming thin gas jet will allow us to verify (or disprove) these considerations. In the long-wavelength range down to 30 nm, the XUV output from our guided-beam setup is several times higher than that from the gas jet targets used in our earlier experiments [1] (designed especially for short-wavelength generation below 10 nm).

4 Conclusions

We have demonstrated stable propagation of sub-10-fs laser pulses at on-axis intensity levels in excess of $10^{15}\,\mathrm{W/cm^2}$ in the fundamental transverse mode of a hollow-core waveguide under reversible conditions. Owing to the high damage threshold of fused silica at sub-10-fs pulse durations and the excellent beam-pointing stability of the laser system used, no degradation of the capillary waveguide is observed over extended periods of operation at a 1-kHz repetition rate. Good transmission efficiency ($\approx 50\%$) is preserved for helium gas filling up to pressures as high as 100 mbar. In preliminary experiments we have demonstrated high-harmonic generation down to wavelengths of ≈ 10 nm at a kHz repetition rate. The well-controlled experimental conditions (plane-wave propagation, uniform gas density distribution) and the feasibility of guiding intensities above $10^{15}\,\mathrm{W/cm^2}$ without causing damage make this scheme a promising interaction geometry for coherent short-wavelength generation and high-field experiments.

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