Ionization-assisted guided-wave pulse compression
to extreme peak powers
and single-cycle pulse widths in the mid-infrared

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Ionization-assisted spectral broadening of high-energy 10.6 μm laser pulses in a gas-filled hollow waveguide is shown to yield single-cycle pulses with multiterawatt peak powers in the mid-IR. While the highest quality of pulse compression is achieved in the regime of weak ionization, careful management of complex ionization-assisted spectral broadening of guided-wave fields is the key to compressing the output of advanced high-power mid-IR laser sources to single-cycle pulse widths. © 2010 Optical Society of America

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Rapidly developing laser technologies are pushing the frontiers of ultrafast science and enabling the generation of unprecedentedly short field waveforms [1] and extremely high field intensities [2]. With the laser-to-matter coupling efficiency scaling as $I^{2}$ with field intensity $I$ and radiation wavelength $\lambda$, the search for practical solutions for the generation of high-power ultrafast pulses of long-wavelength radiation is a central problem in extreme-light science, and it has led to a renaissance of mid-IR gas-laser sources [3,4]. The pressure broadening of rovibrational lines in the active medium of CO$_{2}$ lasers is known to provide a sufficiently broad gain band for efficient amplification of picosecond light pulses [5,6]. Gas-laser systems based on this principle have been recently scaled up to the terawatt level of peak powers [3,4], suggesting attractive strategies for relativistic particle acceleration and opening access to interesting new regimes of laser-matter interaction. Still, the gain bands provided by CO$_{2}$ lasers, even at high gas pressures, are generally too narrow to support the generation of few-cycle mid-IR pulses, which limits the utility of high-power CO$_{2}$ laser sources for ultrafast science and technology.

Here, we demonstrate that the spectral broadening of laser pulses in a gas-filled hollow fiber [7] can help compress the 10.6 μm high-energy output of advanced gas-laser systems to few-cycle pulse widths. With accurate management of ionization in both the gas-filled fiber core and the dielectric cladding, this method of pulse compression is shown to offer important advantages over a compression of ultrashort mid-IR pulses in the focused-beam geometry [8], where the field intensity and electron density are much more difficult to control.

Low-loss guidance of mid-IR radiation is possible in a broad class of hollow waveguides, including fibers with polymer, metal, and semiconductor inner coatings [9,10]; hollow waveguides with a cladding made of materials with a refractive index $n$ less than unity [11,12]; as well as recently developed hollow-core photonic bandgap waveguides [13]. Here, we examine nonlinear-optical transformations of high-energy 10.6 μm pulses with a pulse width $\tau_{0}$ of a few picoseconds in a gas-filled hollow waveguide with an $n < 1$ dielectric cladding. Propagation dynamics of laser pulses is modeled with an appropriate modification of the generalized nonlinear Schrödinger equation (GNSE) [14–16], which is solved jointly with the equation for the electron-density dynamics, including photoionization and impact ionization (see, e.g., [16] for details of the model). The photoionization rate for the gas and fiber cladding is calculated with a Keldysh type formalism [17]. The impact ionization in the gas and fiber cladding is simulated using the Drude model type formula [14,15] for the inverse bremsstrahlung cross section. Effects related to the retardation of the electron avalanche are included in the first order in the retardation time $\tau_{imp}$. We consider a hollow fiber filled with xenon with a nonlinear refractive index $n_{2} = 8 \times 10^{-10} (p/p_{atm})$ cm$^2$ W$^{-1}$, $\tau_{imp} = \tau_{e} = 190 p_{atm}/p$ fs ($\tau_{e}$ being the electron collision time, $p$ the pressure of the gas in the hollow fiber, and $p_{atm}$ the atmospheric pressure), and the initial density of neutral species $\rho_{0} = 2.7 \times 10^{19} p_{atm} cm^{-3}$. Because of the long wavelength and large pulse width of input mid-IR laser pulses, impact ionization tends to dominate ionization process on the trailing edge of the laser pulse [see the inset to Fig. 1(a)].

Simulations were performed for a gas-filled hollow waveguide with a BeO cladding (the bandgap is 10.6 eV, $\tau_{e} = 10$ fs, and $n < 1$ within the range of wavelengths $\lambda$ from 8.1 to 13.2 μm [11]). Dispersion and absorption of the cladding were included in our model through the available reference data for the complex dielectric function of BeO [11]. The gas dispersion was included through the Sellmeier formula for xenon. The input light beam was assumed to be optimized for coupling into the fundamental mode. The laser peak powers in simulations were kept below the critical power $P_{c}$ for the Kerr-effect-induced excitation [18] of high-order modes ($P_{c} \approx 1.4$ TW for $p = 1$ atm and $\lambda = 10.6$ μm). Ionization-induced mode coupling [19] started to play a noticeable role in our simulations for electron densities at $\rho \gtrsim 7 \times 10^{14}$ cm$^{-3}$. For a field intensity of 12 TW/cm$^{2}$, such an electron density is achieved far on the trailing edge of the pulse [$t \approx 1.6$ ps in Fig. 1(a) inset], with only a small fraction...
of the laser pulse, carrying less than 2% of its energy, subjected to ionization-induced mode coupling.

Parameters of the gas and the waveguide are chosen in such a way as to avoid the laser-induced damage of the waveguide and to keep the electron density \( \rho \) inside the fiber core well below the critical density \( \rho_c \) [shown by dashed curves in insets to Figs. 1(a) and 1(b)]. Our simulations show that the fiber damage occurs primarily on the input end of the fiber, where a freely propagating laser beam is coupled into a waveguide mode, while the analysis that includes only the fiber damage by the evanescent field of the fundamental fiber mode systematically overestimates the maximum laser intensity that can be coupled into the fiber. With laser pulse parameters chosen to mimic an output of a high-power picosecond CO\(_2\) amplifier, \( \lambda = 10.6 \mu m \) and \( \tau_0 = 2 \) ps, the maximum admissible laser intensity on the axis of the hollow fiber was estimated as 18.5 TW/cm\(^2\) [Fig. 1(b), inset]. In calculations presented below, the maximum field intensity [dashed vertical lines in Figs. 1(a) and 1(b)] is a factor of 1.5 lower than \( I_b \), to avoid fiber damage.

For relatively low field intensities and low gas pressures, the ionization effects remain weak over the entire propagation path of the laser pulse, and have almost no influence on pulse evolution. In this regime, the spectral transformation of laser pulses is dominated by Kerr-effect–induced self-phase modulation. In Fig. 2(a), we present the spectrum and the spectral profile of the group delay for a laser pulse with \( \lambda = 10.6 \mu m, \tau_0 = 2 \) ps, and an input peak power \( P_0 = 0.44 \) TW transmitted...
through a 10-m-long hollow fiber in the regime where ionization effects are already detectable but still quite weak [point A in Figs. 1(a) and 1(b), adjacent to the boundary of the weak-ionization regime]. The bandwidth of the fiber output seen in Fig. 2(a) supports a transform-limited pulse width of 93 fs [dotted-dashed curve in Fig. 3(a)]. The nonlinear phase shift induced by the Kerr effect is dominated by a linear chirp [dashed curve in Fig. 2(a)], which can be efficiently compensated by a standard grating-pair pulse compressor. Linear chirp compensation compresses the fiber output to a pulse width of 100 fs [solid curve in Fig. 3(a)], which corresponds to 2.8 field cycles at \( \lambda = 10.6 \, \mu m \) and is only 7 fs longer than the transform-limited pulse. With the energy of the 100 fs peak in the compressed fiber output estimated as 0.83 J, the peak power of this feature is about 8.3 TW, which is 19 times higher than the input peak power.

For higher input energies and/or higher gas pressures, ionization lowers the transmission of a gas-filled hollow fiber. In this regime, ionization and pulse self-steepening effects modify pulse propagation dynamics, giving rise to an asymmetric spectral broadening [solid curve in Fig. 2(b)] and a complex spectral profile of the group delay [dashed curve in Fig. 2(b)]. An ultrafast buildup of the electron density within the laser pulse tends to blueshift the spectrum of the laser pulse [cf. solid and dotted-dashed curves in Figs. 2(a) and 2(b)]. As the input pulse energy is increased, it becomes progressively more difficult to compress the fiber output by a simple compensation of the linear chirp. The complex phase profile of the fiber output translates into a high-energy prepulse behind the grating-pair compressor [Fig. 3(b)]. We quantify the quality of pulse compression using the ratio \( Q = P_p \tau_p (P_{\text{peak}}/P_0)^{-1} \) of the energy \( P_p \tau_p \) carried by the main, most intense peak in the compressed fiber output \( (P_p \text{ and } \tau_p \text{ being the peak power and the pulse width of this peak, respectively}) \) to the energy \( P_0 \tau_0 \) of the input laser pulse. The pulse-compression quality \( Q \) decreases with the growth in the input pulse intensity [Fig. 1(b)] because of both ionization-induced loss and complex phase shifts [Fig. 2(b)], which cannot be compensated with a grating pair. For an input pulse with \( \lambda = 10.6 \, \mu m \), \( \tau_0 = 2 \, ps \), and \( P_0 = 0.22 \, TW \), the main peak of the compressed output of a 10-m-long hollow fiber [point B in Figs. 1(a) and 1(b)] becomes as short as 33 fs [solid curve in Fig. 3(b)].

The transform-limited pulse width supported by the output spectrum in Fig. 2(b) is 24 fs [dashed curve in Fig. 3(b)], i.e., shorter than one field cycle. The energy carried by this peak is 65 mJ, corresponding to a peak power of 2 TW. Even shorter pulses can be generated by using longer hollow fibers, which, however, may add to the complexity of experimental implementation of this pulse-compression technique.

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