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Multioctave supercontinua from shock-coupled soliton self-compression

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Fiber-optic multioctave supercontinuum generation is a unique resource for ultrafast optical science, enabling ultrabroadband frequency-comb technologies and paving the way for the photonics of subcycle field waveforms. Extension of these methods to the mid-infrared encounters numerous challenges, calling for radically new approaches in fiber optics and short-pulse generation technologies, as well as for closing the gaps in our understanding of optical nonlinearities in the mid-infrared. Here, we confront these challenges by showing that multioctave supercontinua spanning from the ultraviolet to the mid-infrared can be generated by shock-wave-coupled soliton self-compression of ultrashort mid-infrared pulses in a gas-filled antiresonance-guiding hollow-core photonic-crystal fiber. Analysis of the fiber output spectra, measured within a broad range of gas pressures and input driver energies, shows that multioctave supercontinuum generation in this setting becomes possible due to soliton self-compression

coupled to shock-wave pulse self-steepening, yielding an extraordinarily short, sub-half-cycle field transients.

INTRODUCTION

Multioctave field waveforms are at the forefront of the rapidly growing field of subcycle pulse generation [1] and coherent lightwave synthesis [2], providing a powerful resource for frequency-comb technologies [3] and enabling time-resolved studies of fundamental electronic dynamics in the gas phase and condensed matter on an extremely fast time scale [4, 5]. Efficient fiber-optic methods of multioctave supercontinuum generation have been developed in the near-infrared spectral range [6, 7], where broadband laser gain media are available and can be integrated with advanced fiber-optic solutions [8] on a compact platform providing a unique combination of extremely low loss, tailored dispersion, and remarkably high optical nonlinearity.

Extension of these concepts and technologies to the mid-infrared spectral range is challenging as it calls for new fiber solutions that would allow a high optical nonlinearity in the mid-IR to be combined with broadband transmission and suitably tailored dispersion. Kagome-cladding [9, 10] and antiresonance-guiding single-ring (SR) [11, 12] hollow-core (HC) photonic-crystal fibers (PCFs) stand out as examples of fiber designs that can provide this unique combination of properties. Recent experiments have demonstrated that the fibers of this class can support multioctave supercontinuum generation as a part of the spectral broadening of ultrashort near-IR laser pulses [13 - 16]. The potential of supercontinuum transformation of ultrashort mid-IR pulses in such fibers is, however, much less understood. Recent experimental studies of an SR HC PCF driven by mid-IR pulses [17] are highly encouraging, as they convincingly demonstrate that such fibers can enable an efficient soliton self-compression of sub-100-fs 3.25- μm pulses, giving rise to 1.35-cycle mid-IR field waveforms.

Here, we explore the ways toward fiber-based generation of even broader supercontinua and pulse self-compression to even shorter field waveforms in the mid-IR. In experiments presented in this paper, ultrashort mid-IR pulses are used to drive supercontinuum generation in a gas-filled SR HC PCF. The antiresonance-guiding ring structure in this fiber is designed in such a way as to support soliton self-compression of the mid-IR driver to pulse widths well below the field cycle. A solitonic transformation of a 3.2- μm , sub-200-fs output of a multistage optical parametric amplifier (OPA) in such a fiber yields multioctave supercontinua spanning from 0.3 to 4.2 μm .

MATERIALS AND METHODS

Mid-IR driver pulses were generated in our experiments through four-stage optical parametric amplification (OPA) [Fig. 1(a)] pumped by an amplified sub-200-fs, 1030-nm output of a solid-state ytterbium laser regeneratively amplified to a pulse energy up to 1.5 mJ [18, 19]. At the first stage, OPA in an Yb-laser-pumped KTP crystal is seeded by a supercontinuum radiation produced by a 1030-nm pulse split off from the Yb-laser output [Fig. 1(a)]. The idler beam produced as a result of this OPA process is blocked by a screen, installed behind the first-stage KTP crystal, while the signal field, centered at ≈ 1520 nm is used to seed OPA in the second-stage KTP crystal. The idler output of this second OPA stage is blocked again, while the amplified signal seeds OPA in the third KTP crystal to be blocked behind this crystal. The idler output of the third OPA stage is amplified in an Yb-laser-pumped KTA crystal [Fig. 1(a)], to yield a mid-IR pulse with a central wavelength $\lambda_0 \approx 3.2$ μm and an energy up to 100 μJ . This beam is expanded with a telescope [lenses L1 and L2 in Fig. 1(a)] and is coupled into a gas-filled hollow-core PCF. The hollow fiber is placed inside a glass tubing with two high-pressure gas cells on each end [Fig. 1(a)], allowing experiments to be performed within a broad range of gas pressures.

A system of three spectrometers, is used to provide an accurate spectral characterization of the hollow-PCF output within a spectral range of several octaves, from the UV to the mid-IR. For spectral measurements in the UV and visible, the short-wavelength part of the PCF output spectrum is reflected off a 0.5-mm Si plate [Fig. 1(a)] to be spectrally analyzed with an OceanOptics USB4000 spectrometer. A flip mirror [FM in Fig. 1(a)] is then used to direct the beam transmitted through the Si plate to an OceanOptics NIRQuest spectrometer. Finally, the mid-IR part of the hollow-PCF output spectrum is characterized using a homebuilt spectrometer consisting of a scanning monochromator and a thermoelectrically cooled HgCdTe detector. A broadband infrared tungsten bulb is used for accurate detector calibration. Temporal envelopes and phases of the mid-IR driver are characterized using frequency-resolved optical gating (FROG) based on second-harmonic generation (SHG) in a 0.5-mm-thick AgGaS₂ crystal. A LiTaO₃ beam profile analyzer, placed behind a silicon plate, blocking radiation with wavelengths shorter than ≈ 1.1 μJ , is used to measure the field intensity distribution across the supercontinuum fiber output.

Soliton self-compression to subcycle pulse widths requires a waveguide providing a high transmission and anomalous dispersion within a broad bandwidth around the central wavelength of the driver. To meet these requirements, we chose to work with an antiresonance-guiding single-ring hollow PCF [Fig. 1(b)] [11, 12]. A suitable combination of transmission and dispersion properties is achieved with a PCF design [Fig. 1(b)] where a hollow core with a diameter $D_c \approx 70 \mu\text{m}$ is bounded by an array of six identical silica rings, each having a diameter $d \approx 37 \mu\text{m}$ and a wall with a thickness of $t \approx 0.59 \mu\text{m}$. The choice of the thickness of rings in the antiresonance-guiding structure [Fig. 1(b)] is critical for the ability of the fiber support compression to subcycle pulse widths. The spectra of waveguide loss and group-velocity dispersion for this fiber, measured experimentally (brown solid line) and calculated with the use of the Zeisberger–Schmidt model [20] (grey shading), are shown in Fig. 1(c). The fiber provides a high transmission and anomalous dispersion [solid lines in Fig. 1(c)] within the entire spectrum of the OPA output [blue shading in Fig. 1(c)], allowing the 3.2- μm sub-200-fs OPA pulses to be coupled into solitons. On a larger scale, the transmission spectrum of the fiber is piecewise-continuous, comprising back-to-back transmission bands with a broadband dispersion anomaly within each of these bands [Fig. 1(c)].

RESULTS AND DISCUSSION

The spectra of the hollow-PCF output measured as a function of the input energy of the mid-IR driver W_0 for a fixed gas pressure, $p \approx 5$ bar, are presented in Fig. 2(a). For low W_0 , mid-IR pulses transmitted through the fiber display an almost symmetric spectral broadening, indicating the dominant role of self-phase modulation (SPM). The bandwidth of the fiber output increases with growing W_0 . For $W_0 > 27 \mu\text{J}$, the third and fifth harmonics of the mid-IR driver become easily detectable at central wavelengths 1055 and 633 nm [Fig. 2(a)]. With a further increase in W_0 , the spectra of optical harmonics merge together with the high-frequency wing of the broadened spectrum of the driver, giving rise to a multioctave supercontinuum for $W_0 > 37 \mu\text{J}$. A typical spectrum of the supercontinuum PCF output measured with $W_0 \approx 45 \mu\text{J}$ and $p \approx 5$ bar spans from approximately 300 nm to 4.2 μm [Fig. 2(a)]. At this level of driver energies, PCF output spectra are seen to exhibit a strong blue shifting, indicating the significance of self-steepening and ionization-induced phase shifts.

Similar tendencies are observed when the PCF output spectra are measured as a function of the gas pressure [Fig. 2(b)]. As p is increased from 1 to 16 bar, the PCF output spectra display

the same pattern of transformations – from symmetric spectra dominated by basic SPM at low p [$p < 2.5$ bar in Fig. 2(b)] through the spectra with well-resolved third and fifth harmonics [$2.5 < p < 3.6$ bar, Fig. 2(b)] to asymmetric spectra with a strong blue shift at high p [$p > 3.9$ bar, Fig. 2(b)]. A well-resolved peak observed at around a wavelength of $1.25 \mu\text{m}$ for gas pressures above ≈ 4.4 bar (Fig. 2b) originates from four-wave mixing enabled by resonances between the core-guided modes of the PCF and the modes of the capillary walls [16].

In the case of large W_0 and p , the initial stage of a slow, gradual spectral broadening of the driver pulse [within the first 15 - 20 cm in Figs 3(a), 4(d)] is followed, by a stage within which the driver bandwidth tends to build up in a dramatic, almost explosion-like manner, gaining more than an octave within just a few centimeters [$22 < z < 25$ cm in Fig. 3(a)]. In experiments, the location of this explosion-like supercontinuum buildup can be determined from a clearly defined boundary of visible emission through the side wall of the fiber [Figs. 5(a), 5(b)]. In Fig. 3(a), the location of this region in experiments is marked with a vertical dashed line, showing, once again, that numerical simulations agree well with experimental results.

To understand spectral and temporal transformations of an ultrashort mid-IR driver in a hollow PCF, we employ the field-evolution model based on the generalized nonlinear Schrödinger equation (GNSE) [21 - 23] modified to include field-evolution effects related to ultrafast ionization and harmonic generation [24, 25].

To study the evolution of ultrashort laser pulses toward subcycle field waveforms, we represent the GNSE for the electric field as

$$\begin{aligned} \frac{\partial}{\partial z} A(\omega, z) = & i\tilde{D}(\omega)A(\omega, z) - \alpha(\omega)A(\omega, z) \\ & + i\frac{\omega}{c}\tilde{F}\left\{\left[n_2 I(\eta, z) + \frac{\chi^{(3)}}{4n_0^2 c \epsilon_0} A^2(\eta, z)\right]A(\eta, z)\right\} \\ & - \tilde{F}\left\{\frac{U_i W(\rho_0 - \rho(\eta, z))}{2I} A(\eta, z)\right\} \\ & - \left(\frac{i\omega_0^2 \omega}{2cn_0 \rho_c (\omega^2 + \tau_c^{-2})} + \frac{\sigma(\omega)}{2}\right)\tilde{F}[\rho(\eta, z)A(\eta, z)] \end{aligned} \quad (1)$$

Here, $A(\eta, z) = (2n_0)(c\mu_0)^{-1} \int_0^\infty E(\omega, z)e^{-i\omega\eta} d\omega$, $E(\eta, z)$ is the physical, real-valued electric field, $A(\omega, z)$ is its Fourier transform, η is the retarded time, ω is the frequency, z is the propagation coordinate, $I(\eta, z) = |A(\eta, z)|^2$ is the field intensity, $\tilde{D} = \beta(\omega) - \omega/v_g$ is the dispersion operator, $v_g = (\partial\beta/\partial\omega|_{\omega_0})^{-1}$, $\beta(\omega)$ is the propagation constant, ω_0 is the central frequency of the input laser

field, $\chi^{(3)}$ is the third-order nonlinear-optical susceptibility, $\alpha(\omega)$ is the linear loss due to the mode leakage, $\tilde{F}$ is the Fourier transform operator, c is the speed of light in vacuum, n_0 is the refractive index at the frequency ω_0 , ρ is the electron density, $W(I)$ is the photoionization rate, $U_i = U_0 + U_{\text{osc}}$, U_0 is the ionization potential, U_{osc} is the energy of field-induced electron quiver motion, $\rho_c = \omega_0^2 m_e \epsilon_0 / e^2$ is the critical plasma density, m_e and e are the electron mass and charge, respectively, ρ_0 is the initial density of neutral species, and σ is the inverse bremsstrahlung cross section.

This generalization of the nonlinear Schrödinger equation (NSE) includes all the key physical phenomena that have been identified as significant factors behind the guided-wave evolution of ultrashort mid-IR pulses – dispersion, linear waveguide loss, Kerr nonlinearities, harmonic generation, pulse self-steepening, as well as ionization-induced loss, dispersion, and optical nonlinearities. The field evolution equation [Eq. (1)] is solved jointly with the equation for the electron-density buildup,

$$\partial \rho / \partial \eta = W(I) + \sigma(\omega_0) U_i^{-1} \rho I, \quad (2)$$

which includes photoionization and impact ionization, with the photoionization rate $W(I)$ calculated using the Popov–Perelomov–Terentyev modification of the Keldysh formalism [26, 27] and the inverse bremsstrahlung cross section σ included through the Drude-model formula $\sigma(\omega) = e^2 \tau_c [m_e \epsilon_0 n_0 c (1 + \omega^2 \tau_c^2)]^{-1}$, where τ_c is the collision time.

The input laser field is defined in simulations in such a way as to model the temporal envelope and the spectrum [grey shading in Fig. 2(a)] of the 3.2- μm driver used in our experiments. For experiments with an argon-filled hollow PCF, the Kerr-effect nonlinear refractive index is $n_2 \approx 1.1 \times 10^{-19} (p/p_0) \text{ cm}^2/\text{W}$, p_0 is the atmospheric pressure, and the cubic susceptibility responsible for third-harmonic generation, and $\chi^{(3)} \approx 7.5 \cdot 10^{-22} (p/p_0) \text{ cm}^2/\text{V}^2$. The ionization potential of argon is $U_0 \approx 15.76 \text{ eV}$ and the Drude-model collision time is $\tau_c \approx 190 (p_0/p) \text{ fs}$.

Given the multioctave bandwidth of the supercontinuum PCF output in our experiments, our description of the Kerr nonlinearity in terms of a frequency- and intensity-independent coefficient n_2 is, of course, a simplification. Both dispersion and intensity dependence of the Kerr-effect nonlinear response should be included [28 – 30] for a more rigorous analysis of such broad supercontinua generated within such a broad range of field intensities and gas pressures. However, closed-form models integrating field evolution equations jointly with equations for the frequency- and intensity-dependent nonlinear response are yet to be developed.

The maps in Fig. 3(a) illustrate the spectral transformation of a mid-IR driver in a hollow PCF calculated as a function of W_0 . These maps are instructive in showing how mid-IR pulses tend to develop a blue shift due to pulse-self-steepening and ionization-induced change in the refractive index as they propagate along the hollow PCF in the high- W_0 and/or high- p regime. The spectra of the mid-IR pulse at the output of the PCF [$z = 31$ cm in Figs. 2 and 4(a)] are seen to agree very well with the measured PCF output spectra [cf. solid curves and the spectra given by blue shading in Figs. 2, 4(a)].

With the predictive power of our model confirmed, we are in a position to analyze the maps of temporal evolution of mid-IR pulses [Fig. 3(b)]. Pulse self-compression is perhaps the most prominent tendency readily observed in all these maps. However, parameters of this self-compression dynamics – most importantly, the minimum pulse width achieved within the PCF and the length of maximum pulse compression – are strongly sensitive to W_0 and p . In the case of low W_0 and p , the pulse width τ_p of the mid-IR driver monotonically decreases as the pulse propagates toward the fiber output. For higher W_0 and p , on the other hand, $\tau_p(z)$ displays well-resolved oscillation cycles [Figs. 3(b), 4(e)], typical of breathing soliton dynamics [21, 25].

In Fig. 6, we compare the dynamics of ideal solitons [Figs. 6(a), 6(e)], defined as solutions to the NSE, with the dynamics of a mid-IR pulse in our hollow PCF simulated using the full GNSE [Figs. 6(d), 6(h)], as well as the GNSE without the ionization and/or self-steepening terms [Figs. 6(b), 6(c), 6(f), 6(g)]. The dynamics of ideal solitons is controlled by the soliton number $N = (l_d/l_{nl})^{1/2}$, where $l_d = \tau^2/|\beta_2|$, l_d is the dispersion length, $l_{nl} = \lambda(2\pi n_2 I)^{-1}$ is the nonlinear length, τ is the pulse width, β_2 is the group-velocity dispersion coefficient, and λ is the wavelength.

An ideal NSE soliton is seen to display a well-known breathing dynamics with recurring cycles of pulse self-compression and pulse stretching [Figs. 6(a), 6(e)]. High-order dispersion modifies this dynamics [25], leading to soliton fission [31] and decreasing the self-compression length [Figs. 6(b), 6(f)]. As the pulse width approaches the field cycle in the process of soliton self-compression, shock-wave effects start to play a noticeable role, steepening the trailing edge of the pulse [Fig. 6(h)] and giving rise to an additional blue shift in the frequency domain [Fig. 6(d)].

At higher W_0 and p , soliton self-compression occurs within shorter propagation lengths and gives rise to shorter and more intense field transients, enhancing pulse self-steepening and related spectral blue shifting. However, at the level of W_0 and p required for soliton self-compression to sub-cycle pulse widths, ionization effects start to play an significant role [Figs.

6(c), 6(g)]. Ultrafast ionization in itself can induce a strong blue shift, giving rise to important effects in the dynamics of few-cycle solitons in gas-filled hollow PCFs [32 – 36]. However, in the physical scenario where soliton self-compression acts jointly with pulse self-steepening to yield subcycle field transients, ultrafast ionization acts as an important limiting mechanism, inducing significant energy loss. In Figs. 5(c) and 5(d), we present the transmission of the hollow PCF measured (circles connected with solid lines) and calculated (the dashed line) as a function of the gas pressure [Fig. 5(c)] and the input driver energy [Fig. 5(d)]. In the regime of high W_0 and p , the fiber transmission is seen to drop from the low- W_0 , low- p level of about 73% to about 30% for $W_0 \approx 45 \mu\text{J}$ and $p \approx 4.7$ bar. Ionization-induced energy loss lowers the peak power of the solitons, eventually reducing, rather than enhancing, the overall blue shift and limiting the minimum pulse width attainable at the point of maximum self-compression.

Other channels whereby radiation energy can be lost in the high- p , high- W_0 regime may include excitation of higher-order core modes, as well as a leakage through cladding, tunneling, or radiation modes [37]. As a prominent example of such a loss, phase-matching between the core-guided modes of the PCF and the modes of the capillary walls [16] enables a four-wave mixing of these modes, giving rise to a well-resolved peak at around $1.25 \mu\text{m}$ observed in the supercontinuum spectra measured for $p \approx 4.2$ bar (Fig. 2b). The energy of this peak, however, never exceeds 3% of the total energy of output supercontinuum radiation, which is too low to account for the $\sim 70\%$ loss observed in the high- p , high- W_0 regime. This result is consistent with numerical simulations performed with all the fiber loss disabled, suggesting that energy loss through radiation leakage from the PCF core-guided mode remains below 2 – 3% in all the regimes realized in our experiments.

Simulations presented in Fig. 6 show that the transmission and dispersion provided by the hollow PCF used in our experiments are well suited for soliton self-compression to pulse widths well below the field cycle. At sufficiently high W_0 and p , solitons are seen to undergo self-compression cycles [Fig. 6(h)], yielding field waveform transients with a pulse width shorter than the field half-cycle as a part of this oscillatory dynamics. In the frequency domain, these sub-half-cycle soliton transients manifest themselves as multioctave supercontinua, detectable at the fiber output [Fig. 6(d)].

In Fig. 4(a) we present the spectrum of one of such supercontinua, measured at the output of a 31-cm PCF in an experiment with $W_0 \approx 35 \mu\text{J}$ and $p \approx 16$ bar. Beam-profile analysis performed on the supercontinuum PCF output reveals a smooth field intensity distribution [Fig. 4(b)]. Far-

field intensity profiles are in no way fully conclusive of the modal content of the entire supercontinuum output. However, when combined with the analysis of waveguide loss [38], showing that the loss of the fundamental core mode is almost two orders of magnitude lower than the loss of higher-order modes, these results are consistent with a scenario where the supercontinuum is predominantly generated in the fundamental fiber mode.

Field evolution behind the generation of this supercontinuum [Figs. 4(d), 4(e)] involves soliton self-compression that, at $z_c = 31$ cm, yields a field transient with an FWHM pulse width of the central peak as short as $\tau_c = 2.2$ fs [Fig. 4(c)], corresponding to 0.31 of the field cycle at the central wavelength of this field waveform, $\lambda_c = 2.1$ μm . The energy of this 2.2-fs peak is about 5 μJ ($\approx 30\%$ of the total energy of the compressed pulse at $z_c = 31$ cm), corresponding to a peak power of 1.2 GW.

The fiber design is critical for its ability to support soliton self-compression to subcycle pulse widths. To illustrate this argument, we compare, in Fig. 7, the pulse-compression performance of a single-ring hollow PCF whose design and parameters are as specified above with that of a fiber with the same design, but with a slightly larger core diameter D_c and different wall thickness t of the rings forming the antiresonance-guiding structure [Fig. 1(b)]. In the second PCF, instead of $D_c \approx 70$ μm and $t = 0.59$ μm , as in hollow PCFs used in our experiments, we choose $D_c \approx 88$ μm and $t = 1.1$ μm , as in the hollow PCFs used in earlier experiments by Elu et al. [39]. The length of the second fiber, $L = 17$ cm, as well as the pressure of argon, $p = 12$ bar, and the input driver energy, $W_0 = 65$ μJ , are all taken in such a way as to mimic parameters of earlier experiments [39].

As can be seen from Figs. 7(a) and 7(b), the fiber dispersion profile is highly sensitive to the ring wall thickness t . An increase in t shifts the ring resonances, narrowing both transmission bands and regions of anomalous dispersion. Especially damaging is the ring resonance at 2.4 μm , observed in transmission and dispersion of the $t = 1.1$ μm PCF, which strongly suppresses the spectral broadening of the mid-IR driver beyond 2 μm [Fig. 7(d)], limiting the minimum pulse width to $\tau_m \approx 14.5$ fs [Fig. 7(f)]. This τ_m value in our simulations agrees very well with the compressed pulse width achieved by Elu et al. [39]. Moreover, as can be seen from Figs. 7(d) and 7(f), results of simulations for the spectrum and the temporal envelope of the compressed pulse at the output of the hollow PCF with $t = 1.1$ μm agree reasonably well with the results of experiments by Elu et al. [39].

CONCLUSION

To summarize, we have shown that multi-octave supercontinua spanning over the wavelength range from 0.3 to 4.2 μm can be generated through an accurately tailored soliton transformation of 3.2- μm , sub-200-fs pulses in a gas-filled SR HC PCF. The antiresonance-guiding ring structure in this fiber is designed in such a way as to support soliton self-compression of the mid-IR driver to pulse widths well below the field cycle. Analysis of the fiber output spectra, measured within a broad range of gas pressures and input driver energies, shows that multi-octave supercontinuum generation in this setting becomes possible due to soliton self-compression coupled to shock-wave pulse self-steepening, yielding an extraordinarily short, sub-half-cycle field transients.

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FIG. 1. (a) Experimental setup: Yb/Yb: CaF₂, femtosecond front end consisting of a solid-state ytterbium oscillator and an Yb: CaF₂ regenerative amplifier; SC, supercontinuum radiation; L1 – L6, lenses; P, grating polarizer; PCF, hollow-core photonic-crystal fiber; PM, parabolic mirror; FM, flip mirror; LP, longpass filter with a cut-on wavelength of 3.6 μm; BA, beam analyzer. (b) Scanning-electron-microscope image of the hollow PCF. (c) Group velocity dispersion of the single-ring hollow PCF filled with argon at the pressure $p = 0$ bar (blue solid line), 5 bar (pink dashed line), and 16 bar (green dash-dotted line). Also shown is the spectrum of the fiber loss: (brown dotted line) experiments and (grey shading) calculations. Also shown is the spectrum of the mid-IR OPA output used as a driver pulse.

FIG. 2. Spectra of the hollow-PCF output (a) as a function of the input energy of the mid-IR driver W_0 with $p \approx 4.9$ bar and (b) as a function of the argon pressure p with $W_0 \approx 47$ μJ : (solid line) experiment, (blue shading) simulations. The input spectrum of the driver is shown by grey shading.

FIG. 3. (a, b) The maps of (a) spectral and (b) temporal transformation of a mid-IR driver in a hollow PCF for different input energies of the mid-IR driver W_0 with $p \approx 4.9$ bar. The vertical dashed line shows the boundary of visible emission through the side wall of the fiber in experiments. (c) Simulated compressed field waveforms at the fiber output. Temporal envelopes are shown with a dashed line.

FIG. 4. (a) The spectrum at the output of a 31-cm hollow PCF filled with argon at $p \approx 16$ bar with $W_0 \approx 35$ μJ : (solid line) experiment, (blue shading) simulations. The input spectrum of the driver is shown by grey shading. (b) The fiber output beam profile in the far field. One dimensional profiles along $x = 0$ and $y = 0$ are shown by dashed lines. (c) Simulated compressed field waveform at the output of a 31-cm PCF in an experiment with $W_0 \approx 35$ μJ and $p \approx 16$ bar. The temporal waveform is shown with a dashed line. (d, e) The maps of (d) spectral and (e) temporal transformation of a mid-IR driver in the hollow PCF.

FIG. 5. (a, b) The output end of the argon-filled hollow PCF, emitting visible light through its side wall, with (a) $W_0 \approx 41 \mu\text{J}$ and $p \approx 4.9$ bar and (b) $W_0 \approx 46 \mu\text{J}$ and $p \approx 4.9$ bar. (c, d) Transmission of the hollow PCF measured (circles connected with solid lines) and calculated (the dashed line) as a function of (c) the gas pressure with $W_0 \approx 47 \mu\text{J}$ and (d) the input driver energy with $p \approx 4.9$ bar.

FIG. 6. Spectral (a - d) and temporal (e - h) evolution of a mid-IR pulse with $W_0 = 42 \mu\text{J}$ in a single-ring hollow PCF filled with argon at $p \approx 4.9$ bar simulated by solving (a, e) the NSE, (b, f) the GNSE without the ionization and self-steepening terms, (c, g) the GNSE without the self-steepening term, and (d, h) the full GNSE.

FIG. 7. (a, b) Dispersion of a single-ring hollow PCF with a fiber design as shown in Fig. 1(b) with $D_c \approx 70 \mu\text{m}$, $t \approx 0.59 \mu\text{m}$ (a) and $D_c \approx 88 \mu\text{m}$, $1.1 \mu\text{m}$ (b) calculated with the use of the Zeisberger – Schmidt model. The input driver spectrum is shown by grey shading. The spectrum (c, d) and temporal envelope (e, f) of the mid-IR pulse at the output of the hollow PCF with $D_c \approx 70 \mu\text{m}$, $t = 0.59 \mu\text{m}$ (c, e) and $D_c \approx 88 \mu\text{m}$, $t = 1.1 \mu\text{m}$ (d, f): (blue solid line) simulations and (pink dashed line) experiment [34]. The fiber is filled with argon at $p = 12$ bar. The input driver energy is $W_0 = 40 \mu\text{J}$ (c, e) and $65 \mu\text{J}$ (d, f). The input pulse width is 100 fs. The fiber length is 15 cm (c, e) and 17 cm (d, f).