Microjoule-Level Mid-Infrared Femtosecond Pulse Generation in Hollow-Core Fibers

Ang Deng, Trivikramarao Gavara, Muhammad Rosdi Abu Hassan, Daiqi Xiong, Md Imran Hasan, and Wonkeun Chang*

A fiber-based approach that generates mid-infrared femtosecond pulses in the 3–4 μm spectral region with microjoule-level single pulse energy is demonstrated. This is realized in a piece of gas-filled antiresonant hollow-core fiber that is pumped by a two-micron light source. A rapid variation of the dispersion near a structural resonance of the fiber creates a phase-matching point in mid-infrared, which mediates the frequency-down conversion. Femtosecond pulses centered at 3.16 μm wavelength with the pulse energy of more than 1 μJ are generated, achieving a conversion efficiency as high as 8.2%. The emission wavelength is determined solely by the dielectric wall thickness of cladding elements, while the yield is subject to other experimental parameters. This, combined with high power-handling capability of hollow-core fibers, makes it possible to power scale the mid-infrared output by either increasing the pulse energy or repetition rate of the pump. The technique presents a new pathway to build an all-fiber-based mid-infrared supercontinuum source, which promises to be a powerful new tool for ultrahigh sensitivity molecular spectroscopy.

1. Introduction

High-power ultrafast light sources have become an indispensable tool in science and technology. Most powerful laser systems generating femtosecond pulses operate around one-micron wavelength with available average output power in the kilowatts level. [1] The two-micron region is also gaining a lot of attention lately, emerging as a new wavelength for high-throughput ultrafast lasers. [2] Toward the longer wavelength, however, the available power drops dramatically. The lack of powerful ultrafast sources in mid-infrared (mid-IR) stands in stark contrast to their many applications. Highly concentrated mid-IR photons are attractive for triggering extreme nonlinear effects such as high-harmonic generation. [3] Moreover, they can efficiently drive coherent mid-IR supercontinuum generation, [4] offering a unique opportunity in molecular spectroscopy. [5] With a high photon flux mid-IR supercontinuum source, the “fingerprints” of various molecules can be identified in a single measurement at unprecedented sensitivity.

A common solution to generate femtosecond mid-IR pulses rely on optical parametric processes in nonlinear crystals. [6] It allows the generation of wavelengths that are difficult to access directly with lasers due to the lack of suitable gain media. While the technique is largely successful, yielding sub-hundred femtosecond mid-IR pulses at multi-watt-level average output power or millijoule-level single pulse energy, [7,8] it has a major drawback of being prone to vibrations and other environmental variations. This is due to the use of free-space optics, where beam alignment becomes critical for achieving good conversion. Fiber-based systems have the advantage in this regard, but silica—commonly used material for optical fibers—is not transparent beyond 2.4 μm. A recent progress made in modelocked lasers incorporating erbium-, holmium-, or dysprosium-doped fluoride fiber marks a breakthrough in ultrafast mid-IR light source development. [9–12] These systems are capable of delivering pulses in the three-micron region with the nanojoule-level pulse energy and sub-picosecond pulse duration.

Another platform that is attracting growing interest in mid-IR photonics is hollow-core fibers. [13–15] In a hollow-core fiber, light is guided in its central hollow region, bypassing the limitations imposed by the intrinsic properties of waveguide material. It enables low-loss mid-IR transmission even in silica-based optical fibers. An interesting prospect is then to use hollow-core fiber as a container for matter particles to induce lasing at or frequency conversion to mid-IR wavelengths. [16–20] Many demonstrations have been made in the last decade on using gas-filled kagomé-lattice, antiresonant, or simple capillary hollow-core fibers to achieve phase-matched conversion of near-infrared pump to, mostly, the ultraviolet region. [21–25] This is due to the general landscape of dispersion in these fibers, which permits soliton-dispersive wave phase matching only in the blue-side. It is reported that phase matching to mid-IR is possible in gas-filled...
hollow-core fiber by exploiting the photoionization effect, albeit with rather poor efficiency.\[26\]

One promising approach is to utilize so-called the band-edge effect in antiresonant hollow-core fibers (AR-HCFs).\[27\] It exploits the effect of structural resonances in AR-HCF, which dominates and overrules the dispersion profile around them. The concept has been tested in a recent experiment, successfully frequency-downshifting the pump at 800 nm to 1.45 \(\mu\text{m}\), that is, to a wavelength determined by the fiber geometry.\[28\]

Here, we demonstrate a fiber-based ultrafast mid-IR light source based on the band-edge effect. Namely, we produce record-breaking microjoule-level femtosecond pulses centered at 3.16 \(\mu\text{m}\) that emerge from an argon-filled AR-HCF pumped at 2 \(\mu\text{m}\) with the conversion efficiency as high as 8.2\%. The achieved peak power is over three orders of magnitude higher than those reported beyond 3 \(\mu\text{m}\) in optical fibers so far. The emission wavelength can be engineered over a wide spectral range by tuning the fiber geometry. This simple technique offers a potential avenue to realize all-fiberized mid-IR femtosecond source that is compact and robust, yet matches the power performance of optical parametric amplifiers.

2. Results

The frequency conversion is staged in a gas-filled AR-HCF. Figure 1a presents a cross-section of the fiber used. It consists of seven silica tubular cladding elements, which have an average outer diameter \(d = 24 \mu\text{m}\) and wall thickness \(t = 1.4 \mu\text{m}\). The light is guided in the hollow core of diameter \(D = 73 \mu\text{m}\). Inhibition of coupling between spatial modes in the hollow core and those in the cladding ensures that light launched in the core is confined and transmitted along the fiber with minimal leakage.\[29,30\] It turns out dielectric modes in the cladding wall interact the most strongly with core modes, making the wall thickness \(t\) one of the key geometrical parameters in AR-HCF guidance. Namely, \(t\) governs resonant bands where light in the core leaks out through coupling to dielectric modes. This occurs at wavelengths given by:\[31\]

\[
\lambda_n = \frac{2 t}{m} \sqrt{n^2 - 1}
\]

where \(n\) is the refractive index of dielectric material, that is, silica, and \(m = 1, 2, 3, \ldots\) is the resonance order. The hollow guidance in the core then happens in low-loss regions between the resonances.

Figure 1b shows the calculated transmission loss of fundamental core mode of an idealized AR-HCF that has the same cross-sectional dimensions as that in Figure 1a. The presence of resonant and antiresonant bands across the spectrum is evident. The normalized transmission spectrum taken at the output of the fiber of length 2 \(\mu\text{m}\) is also plotted in Figure 1b. It matches well with the calculated loss spectrum, as well as the locations of resonances given by Equation (1). The first three loss bands appear in 2.41–2.86 \(\mu\text{m}\), 1.38–1.44 \(\mu\text{m}\), and 0.95–0.97 \(\mu\text{m}\). Hence, the 2 \(\mu\text{m}\)-pump lies in the second transmission window, and the first window covers mid-IR with calculated loss of less than 1 dBm\(^{-1}\) in the 3–5.2 \(\mu\text{m}\) range. The transmission loss of less than 0.35 dBm\(^{-1}\) is measured at 2 \(\mu\text{m}\) using the cut-back method.

The resonances also largely influence group-velocity dispersion (GVD) in their vicinity as shown in Figure 1c. In the central part of each transmission band, GVD closely follows that of a simple dielectric capillary of the same core size and argon pressurization.\[32\] However, it deviates and varies rapidly near the band edges. As we shall see, this dramatic GVD change in the band edges is the key to phase-matched conversion to mid-IR. Note that in the band edges, the \(t\)-induced resonances dominate the dispersion, while gas filling makes only a minor impact. The system exhibits anomalous dispersion at 2 \(\mu\text{m}\) when pressurized with argon at 16 bar, which permits the formation of optical solitons.

The experimental setup is illustrated in Figure 2. The AR-HCF is pressurized with argon. One of the two fiber ends is pumped by 2 \(\mu\text{m}\) idler beam from an optical parametric amplifier that is driven by a Tsapphire laser operating at 1 kHz repetition rate. The pump pulse has 65 fs full width at half maximum (FWHM)
Figure 2. A schematic of the experimental set-up. OPA, optical parametric amplifier; LP, long-pass filter; HWP, half-wave plate; TFP, thin-film polarizer; PM, power meter; SM, spectrometer; MC, monochromator; M, mirror; L, lens.

Figure 3. Mid-IR generation. a) Measured (red-solid line) and simulated (gray shade) spectra at the 25 cm-long AR-HCF output. The fiber is presurized with 16 bar argon and pump pulse energy is 12.5 $\mu$J. The pump spectrum is plotted together for reference (blue-dashed line). The insets are intensity profiles of the total and mid-IR beams emerging from the fiber output characterized using the knife-edge method. b) Simulated spectral evolution along the fiber length. c) The corresponding soliton-dispersive wave phase-matching diagram (blue-solid line). The dephasing of a simple dielectric capillary of the same core size and argon pressurization is included for comparison (red-dashed line). Phase-matching points that originate from the resonant bands (black crosses) and capillary model (red diamond) are marked in the diagram. Only the first three resonant bands, denoted RB1, RB2, and RB3 (magenta shades), are considered in the dephasing diagram and band-edge induced phase-matching points for clarity.

a

b

c

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A numerical simulation of the pulse propagation is carried out for the same set of parameters. Simulated output spectrum shown in Figure 3a exhibits a high level of agreement with the measurement, reproducing most of the spectral details including strong mid-IR radiation and other prominent peaks around 1.45 and 0.35 $\mu$m. These features appear due to phase matching between soliton and dispersive waves, which leads to coherent transfer of energy from the pump.[33] A false color map of the spectral evolution along the fiber length is presented in Figure 3b. The 12.5 $\mu$J pump, which amounts to a higher-order soliton of order 2.7, initially undergoes temporal compression and spectral broadening due to interplay between anomalous dispersion and spectral broadening due to interplay between anomalous dispersion and nonlinearity. Efficient frequency conversion takes place after 15 cm of propagation in the fiber, when low-intensity spectral tails of the broadened pump eventually extend to zero phase-mismatch points. Here, these are given by the soliton-dispersive wave phase-matching condition

$$\Delta \beta_{DW} = \beta - \beta_0 - \beta_1 (\omega - \omega_0) - \frac{3 \alpha_0^2}{8c^2} \chi^{(3)} |E_0|^2 = 0$$

where $c$ is the speed of light in free space and $\beta$ is wavevector of the propagating mode in the fiber, $\beta_0$ and $\beta_1$ are the zeroth and first Taylor series expansion coefficients of $\beta$ at the pump, $\omega_0$, which are related to phase and group velocities, respectively. The last term in Equation (2) is a nonlinear correction term, where $\chi^{(3)}$ is the third-order susceptibility of filling material and $E_0$ is the peak electric field strength of the pump. Figure 3c is the soliton-dispersive wave phase-matching diagram that results from Equation (2). There are two distinctive origins of phase matchings in this diagram. The first is from the general dispersion landscape of hollow-core fiber. It is responsible for the emission at 0.35 $\mu$m, and the equivalent capillary model also features the same phase matching. The other mechanism is caused by the presence of resonances. The rapid GVD change around each resonance creates a phase-matching point in the long-wavelength side of resonance,
that is, in the blue-edge of transmission band of the same order. All phase-matching points marked in Figure 3c, except for 0.35 μm, are due to the band-edge effect. This includes one at 3.1 μm that is promoting the mid-IR radiation. The band-edge-induced phase matchings do not show up in the capillary model. Since the conversion is a phase-matched process, mid-IR inherits phase stability of the pump when the soliton order is low. We confirm this numerically by calculating the degree of first-order coherence in 50 simulated outputs, each calculated with quantum noise added in the input pulse (Note S3, Supporting Information).

As the pump is converted to mid-IR, the higher-order soliton undergoes a fission into its constituents. The conversion stops when the broken apart solitons walk away from mid-IR due to difference in their group velocities, and there are no more temporal overlaps between the solitons and mid-IR. From this point, mid-IR starts to lose energy due to fiber loss. The proximity of phase-matching point to the resonance and being of longer wavelength mean that the loss is relatively high. Therefore, the optimal fiber length for maximizing mid-IR energy is generally around the soliton fission length. Its accurate value can be determined numerically, which is 25 cm for the above set of experimental parameters. The transmission loss, dispersion, and nonlinearity all play important role in the pulse propagation dynamics, and as such, the right length depends on the choice of fiber geometry, gas species and pressure, as well as pump pulse characteristics.

We characterize the mid-IR pulse from the numerical data. Its temporal intensity and phase profiles are shown in Figure 4. The pulse is centered at 3.1 μm wavelength and has FWHM duration of 123 fs and peak power of 10.6 MW at the fiber output. After its generation at the 15 cm mark, mid-IR travels linearly in room temperature and has FWHM duration and peak power of 123 fs and 10.6 MW, respectively. At its Fourier limit, they are 67 fs and 20.4 MW (gray-dotted line).

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One of the parameters that can be changed easily in experiments is the pump pulse energy. It alters the peak intensity of incoming pulse which in turn affects nonlinear phase accumulation. Figure 5a is a collection of output spectra measured at different pump pulse energies while fixing other settings the same as in Figure 3. The band-edge-induced spectral features at 3.16 and 1.45 μm appear at pump energy as low as 8 μJ. The latter exhibits higher spectral intensity due to its location in the same transmission window with the pump. As the energy increases, the main spectrum around 2 μm broadens, and we start to observe the rise of 0.35 μm peak brought by the capillary model-mediated phase matching. At the same time, energy in mid-IR gradually increases. Figure 5b shows energy in the mid-IR spectral band and corresponding conversion efficiency versus the pump energy. The maximum mid-IR energy observed in the experiments is close to 1.5 μJ when the pump is 30 μJ. A monotonic increase of mid-IR energy right up to the maximum pump used in the experiments suggests that mid-IR pulses of higher energies are achievable by further increasing the pump. The conversion efficiency, on the other hand, tops off at 12.5 μJ-pump, where 8.2% of the energy is converted to mid-IR. At higher pump energy, the mid-IR generation onsets at a shorter propagation distance, and hence it travels a longer length in the lossy fiber leading to a lower efficiency. The pump energy has no meaningful influence on the spectral position of mid-IR band as shown in Figure 5c. This is because dispersion in the band-edge is largely dominated by the nearby resonance, which depends solely on the geometrical parameter, t. Added to that, the nonlinear correction term in Equation (2) makes only a small contribution to overall phase matching. Therefore, the pump energy has a negligible effect on the locations of band-edge-induced phase-matching points. On the contrary, it noticeably affects the bandwidth of mid-IR pulse. The band generally becomes broader with rising pump energy. The enhanced broadening of main spectrum at higher pump pulse energy leads to conversion over a wider spectral range in mid-IR.

The gas pressure is another experimental parameter that can be varied onsite. Changing the pressure alters not only the nonlinearity but also the dispersion of the system. Figure 5d presents output spectra at different argon filling pressures when the pump pulse energy is 18 μJ. We observe general broadening of the main pump spectrum as well as generated spectral bands when the pressure is raised. The observation is similar to increasing the pump pulse energy in Figure 5a, since they both enhance the system nonlinearity. The energy in the mid-IR band is plotted against the pressure in Figure 5e together with the conversion efficiency. The energy transfer to mid-IR increases rapidly when the pressure is varied from 7 to 12 bar and flattens afterward arriving at 1.3 μJ when the pressure is 25 bar. One important remark is that the spectral location of mid-IR emission shifts slightly—over a bandwidth of 3.2 THz from 3.14 and 3.25 μm—with the pressure change as evident in Figure 5f. While the resonance is the main influence on the phase matching in the band-edge, the pressure change can also cause small but observable shift in the vicinity. In comparison, emission at the phase matching supported by the capillary model, that is, the spectral feature marked with arrows in Figure 5d, drifts across a much wider range—over a bandwidth of 236 THz from 0.31 to 0.41 μm—when the pressure is varied from 10 to 25 bar. To shift mid-IR wavelength beyond the small stretch that is attainable with the pressure tuning, we need to use an AR-HCF with a different cladding wall thickness t. To this end, a new set of experiments is carried out with another AR-HCF. Figure 6a is a cross-sectional image of the second fiber. The core and seven silica cladding tubes are smaller than the former, having diameters D = 46 μm and d = 20 μm, respectively. The key parameter, t, is thicker at 1.6 μm. It red-shifts the first resonant

![Figure 4](https://www.advancedsciencenews.com/doi/10.1002/lpor.202300082)

Figure 4. Mid-IR pulse characterization. Temporal intensity (blue-solid line) and phase (red-dashed line) profiles of the simulated mid-IR pulse at the fiber output. The pulse is centered at 3.1 μm wavelength, and it has FWHM duration and peak power of 123 fs and 10.6 MW, respectively. At its Fourier limit, they are 67 fs and 20.4 MW (gray-dotted line).
Figure 5. Pump energy and pressure tuning. a) Output spectra at different pump pulse energies when the fiber is pressurized with argon at 16 bar. b) Energy of mid-IR pulse (blue-solid line) and corresponding conversion efficiency (red-dashed line) versus the pump energy. c) The center wavelength (blue-solid line) and FWHM spectral bandwidth (red-dashed line) of mid-IR pulse versus pump energy. d) Output spectra at different argon pressurizations when the pump pulse energy is 18 μJ. The arrows mark emission due to the capillary model-induced phase matching. e) Energy of mid-IR pulse (blue-solid line) and corresponding conversion efficiency (red-dashed line) versus argon pressure. f) The center wavelength (blue-solid line) and FWHM spectral bandwidth (red-dashed line) of mid-IR pulse versus the argon pressure.

band to 2.6–3.2 μm, while still allowing the 2 μm-pump to propagate in the second transmission window. This choice of fiber is interesting, not just for studying the role of t, but also for showcasing the versatility of this approach over a wide range of D. It illustrates the prospect of energy scaling the system either up or down to generate high-energy mid-IR pulses or reduce the pump requirement. Measured spectrum at the output of a 15 cm-long fiber filled with argon at 15 bar is plotted in Figure 6b. The output pulse energy is 14.4 μJ, which amounts to 15 μJ coupled energy. A mid-IR band of energy 140 nJ, centered at 3.62 μm appears on the long-wavelength side of the first resonant band. Here, mid-IR is exposed to much higher loss than in the earlier experiments due to the smaller core size to wavelength ratio. This results in a significantly poorer conversion efficiency.

For wavelength tuning, we note that it is difficult to precisely achieve an intended t directly from the fiber drawing process. One possible solution is to chemically etch the inner structure using hydrofluoric acid (HF). This corrodes silica in AR-HCF at the nanometer scale, which allows us to fine tune t with minimal impact on other geometrical parameters.[35] The fiber in Figure 6a is etched with HF solution over 15 and 38 h, which for the given concentration and flow rate, thins the wall uniformly along the fiber by 50 and 130 nm to reduce t to 1.55 and 1.47 μm, respectively. The magnified images of thinned walls are presented in Figure 6c. By right, the core diameters in two etched fibers should be slightly enlarged, but the changes are too small to be meaningful. The spectra at the output of two etched AR-HCFs of length 15 cm are plotted in Figure 6b. The argon pressure and pump pulse energy remain the same as those in the unprocessed AR-HCF. The mid-IR wavelengths are blue-shifted accordingly from 3.62 to 3.53 μm and 3.43 μm for the 15 and 38 h-etched AR-HCFs. Note that there are other possible solutions to fine-adjust
The generation of microjoule-level mid-IR femtosecond pulses is demonstrated in gas-filled AR-HCFs. The technique exploits the band-edge effect, which dominates the dispersion landscape around structural resonances of the fiber. The mid-IR emission wavelength is dictated primarily by the location of resonance, hence highlighting the main advantage of this approach; we can induce radiation at a desired wavelength by controlling the wall thickness via, for example, fiber tapering[36] or atomic layer deposition.[37]

### 3. Discussion and Conclusion

The generation of microjoule-level mid-IR femtosecond pulses is demonstrated in gas-filled AR-HCFs. The technique exploits the band-edge effect, which dominates the dispersion landscape around structural resonances of the fiber. The mid-IR emission wavelength is dictated primarily by the location of resonance, hence highlighting the main advantage of this approach; we can induce radiation at a desired wavelength by controlling the wall thickness via, for example, fiber tapering[36] or atomic layer deposition.[37]

The fiber has a core diameter $D = 46\ \mu m$, average outer cladding element diameter $d = 20\ \mu m$, and dielectric wall thickness $t = 1.6\ \mu m$. The fibers are pressurized with 15 bar argon and pump pulse energy is 15 μJ. The input spectrum is plotted together for reference (gray-dash-dotted line). The mid-IR pulses are demonstrated in gas-filled AR-HCFs. The technique exploits the band-edge effect, which dominates the dispersion landscape around structural resonances of the fiber. The mid-IR emission wavelength is dictated primarily by the location of resonance, hence highlighting the main advantage of this approach; we can induce radiation at a desired wavelength by controlling the wall thickness via, for example, fiber tapering[36] or atomic layer deposition.[37]

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### 4. Experimental Section

**Fiber Characterization:** The AR-HCFs used in the experiments were fabricated in Nanyang Technological University. A normalized transmission spectrum was obtained with a supercontinuum laser spanning 0.4–2.4 μm. The broadband input was coupled into the fiber of length 2 m, and the output spectrum was acquired with three optical spectrum analyzers to capture the full spectral range. This was then divided by the source spectrum for the normalization. For the AR-HCF presented in Figure 1, the transmission loss was measured over 1.2–2.4 μm by cutting back the fiber from 28 to 1 m. The loss in the 1.2–1.4 μm range is not shown in Figure 1b as this falls in the low-loss regions of the fiber. The measured loss at 2 μm was less than 0.35 dBm$^{-1}$.

Guiding properties of the fundamental core modes in AR-HCFs were calculated based on their idealized structures. They were constructed on the measured geometrical dimensions in their cross-sectional images taken with a scanning-electron microscope. From these, the complex mode indices were computed using the finite-element method over a wide spectral range. The transmission loss included confinement loss, absorption in the silica,[40] and surface scattering.[41] The linear dispersion took into account waveguide portion obtained from the finite-element modeling, as well as pressure dependent argon gas contribution.[42]

The loss measured using the cut-back method was about an order of magnitude higher than that calculated on an idealized fiber with the same geometrical parameters. The difference was due to various imperfections in the fabricated fiber across its cross-section, as well as along the fiber length. Furthermore, while only the fundamental core mode was considered in the calculations, some portion of the input light activated higher-order modes in the measurements that were not fully filtered out within the cut-back length of 1 m. This added on to the total loss measured.

**Experiment:** A piece of AR-HCF had two gas cells attached at the ends to provide argon pressurization. Each gas cell had a 3 mm-thick CaF$_2$ window for optical access, of which the input side window had...
an antireflection coating covering the 1.8–2.2 μm range. The one in the output gas cell was uncoated.

The input at 2 μm was an idler from an optical parametric amplifier which was pumped by a Ti:sapphire laser at 1 kHz repetition rate. A long-pass filter with a cutoff at 1.5 μm was placed at the output of optical parametric amplifier to filter out the signal at 1.34 μm. The input energy was adjusted with a half-wave plate and thin film polarizer. The light was passed through an iris to enhance its spatial beam quality and coupled into the fiber using a plano-convex lens. All input optics had 2 μm-coating to suppress reflections. The input pulse had FWHM duration of 65 fs just before entering the gas cell as measured in the frequency-resolved optical gating technique.[41] Typical coupling efficiencies were >80% for the fiber with 73 μm core diameter and ≈70% for the one with 46 μm core diameter. The both fibers could easily handle up to at least 50 μJ pump pulse energy over long operation time without causing any damages.

The beam leaving the output gas cell was focused to diagnostics. The total power of output beam was measured with a thermal power meter. For the mid-IR measurement, a long-pass filter with cutoff at 2.45 μm was placed before the power meter. A flat loss of 0.45 dB was assumed as the insertion loss across its passband. The spatial profiles of total and mid-IR output beams were characterized using the knife-edge method.[44] An iterative first-order finite difference technique[45] was applied to numerically differentiate the data when recovering profiles. For spectral measurements, a fiber-coupled CCD-type spectrometer covering the 0.2–1.1 μm range as well as two monochromators were employed. One of the monochromators had a silica photodiode and Peltier-cooled lead selenide photodiode for the 0.2–1.1 μm and 1–5.5 μm regions, respectively. The other monochromator had a Dewar-cooled mercury cadmium telluride photodiode that covered the 2–12 μm range. The data recorded on the CCD-type spectrometer was corrected between 0.24 and 1 μm based on its grating efficiency and photodiode responsivity. The monochromators were intensity calibrated in the region >0.4 μm with high-power calibration light sources. The measurements from these devices were cross-checked and merged. The signal-to-noise ratios of the spectrometer and monochromators were 30 and 50 dB, respectively.

**Pulse Propagation Simulation:** The pulse evolution along the gas-filled hollow-core fiber was simulated by solving a single-mode unidirectional field propagation equation. It is given by[46]

\[
\frac{\partial}{\partial z} E(z, \omega) = \left( \beta - \frac{\omega}{v} + \left( \frac{\alpha}{2} \right) E(z, \omega) + i \frac{\alpha_0}{2\varepsilon_0 c} \right) \left( \chi^{(3)}(z) E(z, \omega)^3 + \frac{\alpha_0}{2\varepsilon_0 c} \right) - \frac{\alpha_0}{2\varepsilon_0 c} \frac{\partial}{\partial \omega} \int \left( N(z', \omega') \frac{i\omega}{2\varepsilon_0 c} \right) E(z', \omega') d\omega'
\]

(3)

where \( \varepsilon_0 \) is the vacuum permittivity, \( v \) is a time frame moving at a reference velocity, \( z \) and \( \omega \) is the propagation length. \( E(z, \omega) \) is an evolving optical field in the frequency domain with \( \omega \) denoting angular frequency. This was obtained by taking the Fourier transformation of the fast oscillating electric field, that is, \( E(z, \omega) = F(E[z, \tau]) \). An ideal hyperbolic-secant function was assumed as the input field amplitude. The linear dispersion of the fundamental core mode of gas-filled hollow-core fiber was accounted for in \( \beta \). The term containing \( \chi^{(3)} \) was responsible for the third-order nonlinearity of pressurized argon.[47] The last term described photoionization which had negligible effect for the cases studied in this work, but was nevertheless included for the sake of completeness. Here, \( I_0 \) is the first ionization energy, and \( e \) and \( m_e \) are the electron charge and mass, respectively. For the calculation of local free-electron density, \( N(z, \tau) \), a model formulated by Ammosov et al. was adopted.[48]

**Supporting Information**

Supporting Information is available from the Wiley Online Library or from the author.

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**Conflict of Interest**

The authors declare no conflict of interest.

**Data Availability Statement**

The data that support the findings of this study are available from the corresponding author upon reasonable request.

**Keywords**

hollow-core fibers, mid-infrared lasers, nonlinear fiber optics, ultrashort pulses

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