

# Deep-Ultraviolet to Mid-Infrared Supercontinuum in Single-Ring Hollow-Core Photonic Crystal Fiber

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**Abstract:** We report the first supercontinuum generated in a gas-filled single-ring hollow-core PCF. When pumped with ultrashort pulses at 1500 nm, the emitted spectrum spans three octaves from the deep ultraviolet to the mid-infrared.

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## 1. Introduction

Broad-band supercontinuum (SC) generation has been widely investigated due to its many applications, such as in spectroscopy or ultrashort pulse synthesis. Photonic crystal fibers (PCFs) have proved to provide an ideal platform for SC generation owing to the longer light-matter interaction lengths achieved as compared to bulk or free-space systems, as well as the possibility of engineering their dispersion [1]. In particular, it is possible to design and fabricate solid-core PCFs with anomalous dispersion at near-infrared wavelengths, thus enabling soliton-related effects such as soliton fission, dispersive wave emission, spectral recoil or modulational instability, all of which contribute to the generation of broad-band SCs [1].

Although silica-based solid-core PCFs have been successfully used for SC generation in the near-infrared and visible regions, extending the SC into the mid-infrared (mid-IR) is limited by the increasing absorption of fused silica at longer wavelengths. In addition, the extension of the SC to the deep ultraviolet (DUV) and beyond is severely impaired by permanent color-center-related damage. To overcome this, it is possible to use different glasses featuring wider transmission windows [2]—or gas-filled hollow-core PCFs (HC-PCFs) [3]. The use of kagomé-PCF [4], in particular, allows easy tuning of the nonlinearity and dispersion of the system through the use of different gas species, or simply by changing the pressure. This enables precise control of the dynamics of SC generation, making gas-filled kagomé-PCFs convenient and versatile SC sources. Recently single-ring HC-PCFs, which like kagomé-PCFs guide by anti-resonant reflection, have been proven to offer low transmission loss in the mid-IR [5].

Here we report the generation of an ultrawide SC in such a single-ring HC-PCF. The broader transmission into the mid-IR, together with shallow dispersion at long wavelengths, allows SC generation to be extended into the mid-IR without harming the quality of the efficient dispersive wave emission in the DUV spectral region.

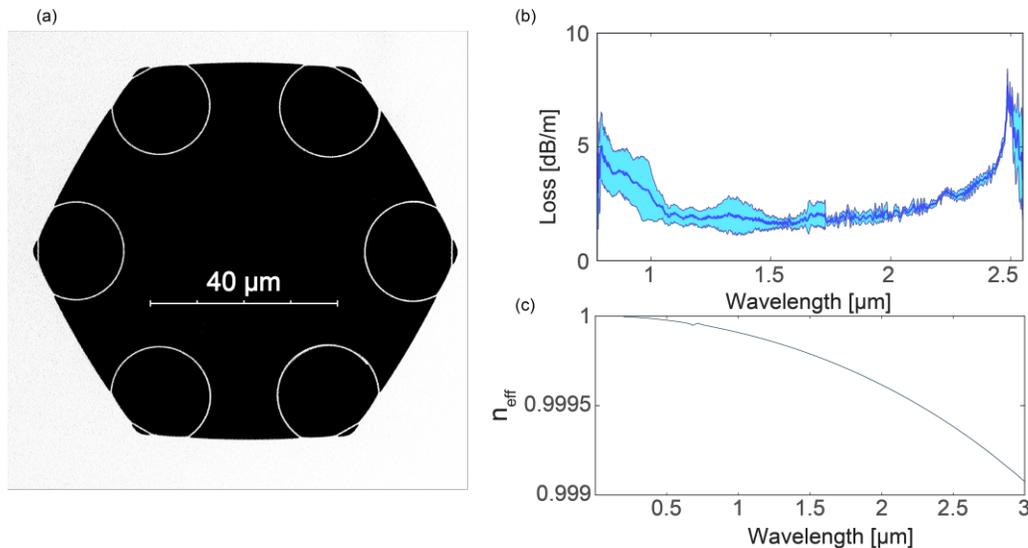


Fig. 1: (a) Scanning electron micrograph of the transverse section of the single-ring fiber used in the experiment; (b) Measured loss of the fiber (solid blue line) and estimated error interval (light blue area) (c) Effective index of the fiber calculated through finite element modeling.

## 2. Single-ring HC-PCF

The microstructure of the single-ring HC-PCF used in the experiments is shown in Fig. 1(a). It consists of a hollow core surrounded by six non-touching silica capillaries arranged within a hexagonal jacket [6-7]. The core diameter is  $\sim 51 \mu\text{m}$  (measured between two opposite capillaries) and the core-wall thickness of the capillaries is  $\sim 340 \text{ nm}$ .

Strongly modal dephasing between the core mode and the modes of the surrounding capillaries creates anti-resonant reflection of core light, preventing leakage of core light into the surrounding glass sheath. Fig. 1(b) shows the measured loss spectrum of the fundamental core mode. As it can be seen, the fiber losses remain below  $\sim 5 \text{ dB/m}$  over a broad wavelength range from 1 to  $2.3 \mu\text{m}$ . Such loss levels are negligible in the experiments we report, which involve fiber lengths of only a few centimeters. The remarkable flatness of this attenuation curve is primarily due to the simple structure of the single-ring fiber, which unlike kagomé-PCF avoids a multiplicity of cladding resonances that can phase-match to the core mode at specific wavelengths, causing localized loss peaks [4]. This behavior is intimately linked to the smooth dispersion profile obtained via finite-element modeling (see Fig. 1(c))—a very convenient feature for SC generation as will be explained in the following section.

## 3. Supercontinuum generation in single-ring HC-PCF: experiment and results

To demonstrate SC generation, we launched  $\sim 10 \mu\text{J}$  pulses centered at  $1.5 \mu\text{m}$ , generated by a commercial OPA system, into a  $\sim 5 \text{ cm}$  long single-ring HC-PCF (transverse structure shown in Fig. 1(a)), filled with argon at 5 bar. From the measured duration of the near-infrared pulses pumping the OPA system, and the bandwidth of the  $1.5 \mu\text{m}$  radiation generated, we estimate the pump pulse duration to be  $\sim 35 \text{ fs}$ . The output spectrum (see Fig. 2) was characterized using two calibrated spectrometers so as to cover the whole range of the SC. At a 30 dB level the SC extends from 200 nm to beyond  $2.5 \mu\text{m}$  (the limit of the measurement range in the set-up). Note that, due to the high energy of the SC compared to solid-core fiber supercontinua, the 30 dB level still represents a high spectral energy density of the order of  $10 \text{ nJ/nm}$ .

Two main features are apparent in the measured SC. The first is the generation of a dispersive wave (DW) in the normal dispersion regime (at 5 bar, the zero-dispersion wavelength of the fiber lies at  $\sim 620 \text{ nm}$ ), which causes the appearance of a strong DUV band peaking at  $240 \text{ nm}$  [8], followed by weaker peaks at even shorter wavelengths possibly due to phase-matching to higher-order fiber modes [9]. The second is the spectral recoil of the pump pulse: As a consequence of the emission of the DW in the DUV and conservation of the total energy of the photons, the carrier frequency of the pump must experience a red-shift, which pushes the SC out to longer wavelengths even in Raman-inactive gases. This phenomenon is indeed expected to be quite strong in large-core single-ring HC-PCFs owing to their relatively low dispersion at long wavelengths [10].

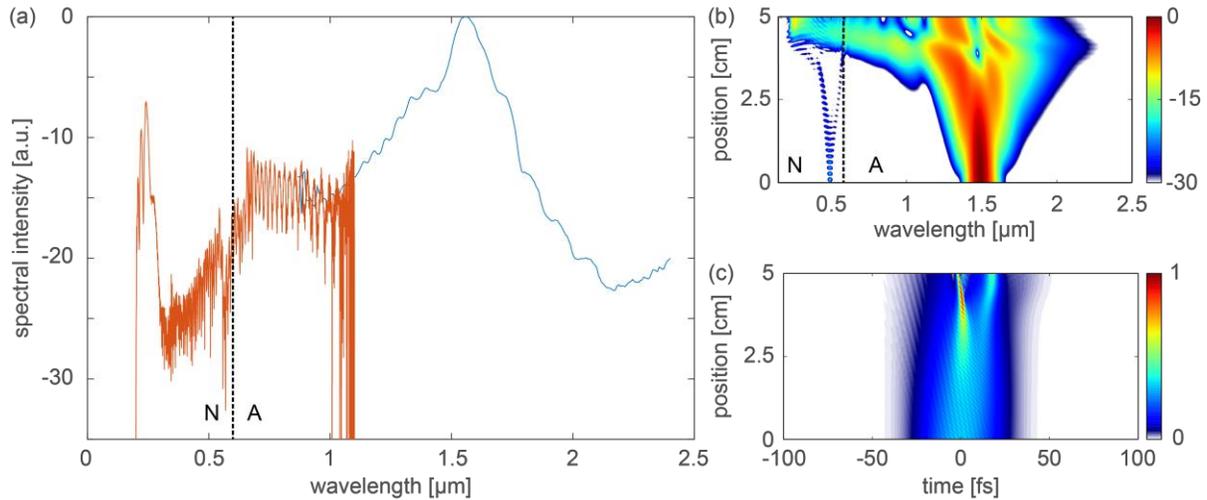


Fig. 2: (a) Supercontinuum generated in a 5-cm-long single-ring HC-PCF filled with argon at 5 bar. The spectrum is characterized through both UV-VIS (red solid line) and NIR-mid-IR (blue solid line) spectrometers. (b-c) Numerically simulated spectral and temporal evolution of the pump pulses inside the single-ring fiber. In Fig. 1(a-b) the dashed line denotes the zero dispersion wavelength, while N and A indicate the regions of normal and anomalous dispersion, respectively.

We have numerically modeled the dynamics of the process using a set of multimode-extended coupled unidirectional pulse propagation equations [9], which account for the linear gas-filled fiber dispersion as well as the

nonlinear polarization created by both the Kerr response of the medium and the free electrons generated via photoionization of the gas filling the fiber core. As we see in Fig. 2(b), the pump pulse launched in the anomalous dispersion regime of the fiber undergoes self-compression until it reaches a sub-cycle duration ( $<5$  fs). At the point of maximum compression, which roughly coincides with the fiber output end in the experiment, a DW is emitted at around 240 nm while the coherent bandwidth of the self-compressed pulse exceeds three octaves, extending from 200 nm to beyond 2  $\mu\text{m}$ , in agreement with the experimental observations (see Fig. 2(a)).

In the experiments, we also observed a clear modulation in the measured spectra over a broad wavelength range. Although this feature is still under investigation, we attribute it to the interference between two delayed ultrashort pulses generated in the fiber through pulse splitting, which occurs at the very last stages of the temporal evolution simulated in Fig. 2(c).

#### 4. Conclusions

A broad supercontinuum spanning more than 3 octaves from the DUV to the mid-IR can be generated in gas-filled anti-reflection-guiding single-ring HC-PCF. Numerical simulations indicate that the mechanism behind this large spectral broadening is soliton self-compression, which implies that the generated bandwidth is fully coherent. The results show that this new type of microstructured fiber, with its low attenuation and favorable dispersion characteristics, provides a promising platform for exploiting soliton dynamics at long wavelengths. Although the results shown here were obtained by pumping the system with ultrashort pulses at 1.5  $\mu\text{m}$ , work is ongoing to study the behavior of the system at longer pump wavelengths ( $\sim 2$   $\mu\text{m}$ ), with possible intriguing applications in the mid-IR spectral region [11].

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