Supercontinuum generation from deep-UV to mid-IR in a noble gas-filled fiber pumped with ultrashort mid-IR pulses

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Abstract: We experimentally demonstrate record multi-octave supercontinuum (SC) generation spanning from 200 up to 4000 nm using a single Ar-filled hollow-core anti-resonant fiber pumped in the mid-IR region for the first time.

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1. Introduction

Hollow-core antiresonant fibers (HC-ARFs) have attracted significant attention over the past few years and are now considered a promising and versatile platform for gas-based ultrafast nonlinear optics [1,2]. These fibers offer strong confinement of the light in the core, accommodate extremely high peak powers, transmit light over a wide bandwidth with low-loss and provide pressure-tunable dispersion and nonlinear characteristics [1,2]. Numerous studies have revealed the true potential of gas-filled HC-ARFs in laser science by demonstrating tunable vacuum- and deep-UV (DUV) sources, enhanced stimulated Raman scattering and frequency comb generation, sub-cycle pulse compression, to mention a few [1-3]. Belli *et al.* for example reported the generation of bright SC generation spanning from about 124 nm up to 1200 nm using a hydrogen-filled HC-ARF pumped at 805 nm wavelength [4]. Köttig *et al.* observed plasma-induced mid-IR dispersive wave (DW) generation in the 3-4 μm wavelength region using two cascaded gas-filled HC-ARF stages pumped at 1030 nm [5]. The aforementioned as well as other reports (see recent review [3]) have already set the scene for a new generation of practical gas-based sources in previously inaccessible spectral regimes. However, most reports on SC generation using gas-filled HC-ARFs are based on pumping the fiber in the visible or near-IR region, while little or no experimental research has been carried out pumping in the mid-IR [6, 7].

In this work, we report for the first time, to the best of our knowledge, record SC generation covering the 200 - 4000 nm spectral range based on a single Ar-filled (30 bar) HC-ARF pumped in the mid-IR region at a central wavelength of 2460 nm [8]. The generated ultrafast soliton-plasma nonlinear dynamics led to efficient soliton self-compression and phase-matched resonant dispersive waves (DWs) emission in the DUV spectral region. Moreover, we briefly discuss how the gas pressure strongly influences the soliton dynamics and consequently the generated SC spectrum.

2. Experiments and Results

The HC-ARF used in the experiments consists of seven non-touching silica capillaries with wall thickness of ~640 nm forming a core diameter of ~ 44 μm as shown in SEM image in Fig 1(a). The calculated mode profiles of the fundamental mode for the pump (2460 nm) and first resonance wavelength (1380 nm) are shown below Fig. 1(a). The fiber was designed to have the first anti-resonance window in the spectral range from 1400 – 4000 nm as shown in Fig.1 (b). The group-velocity dispersion (GVD) β_2 was calculated for different gas pressures based on the finite element method [8]. In addition, the GVD was measured for the evacuated HC-ARF case using a mid-IR SC source (MIR SuperK compact, NKT Photonics A/S).

In order to study the nonlinear dynamics in the fiber, linearly polarized, 100 fs, mid-IR pulses with 1 kHz repetition rate were generated by a tunable difference frequency generation (DFG) laser system. The mid-IR pulses were launched into a 30 cm long HC-ARF mounted between two high-pressure gas cells. The experimental set up is depicted in Fig. 1 (c). The calculated and measured SC spectra spanning from the 200 nm up to 4000 nm for the Ar-filled HC-ARF under 30 bar are presented in Figure 1 (d). The pulse evolution was numerically investigated using the unidirectional field equation [7]. The average output power was measured to be as high as 5 mW when the fiber was pumped with 100 fs pulses having an estimated injected pulse energy of ~8 μJ. The most efficient DW was located at ~275 nm with an estimated energy of 1.42 μJ (corresponding to 28.4 % of the total output power). The nonlinear mechanism behind the observed multi-octave spectral broadening relies upon strong soliton-plasma interaction and it has been extensively described in literature [1-3, 7-9].

Figure 1 (e) shows the spectral evolution for a fixed pump energy while changing the pressure of the gas. During the measurements, it was observed that the visible part of the spectrum was highly dependent on the gas pressure levels even for low pump energies (< 3 μJ output energy). This effect is attributed to the significant changes in the GVD and zero-dispersion wavelength (ZDW) in the visible part of the spectrum compared to mid-IR where limited broadening was observed at such low powers. However, at higher powers the pressure level has a strong influence in the mid-IR regime. Above 15 bar the long-wavelength edge starts to increase together with the energy of the DWs around 275 nm, while simultaneously fading the energy of the DWs around 240 nm. The increasing mid-IR broadening and 275 nm DW generation is attributed to the increase in nonlinearity of the gas with pressure, while the fading 240 nm DW generation is believed to be caused by the red-shifting of the ZDW [8].

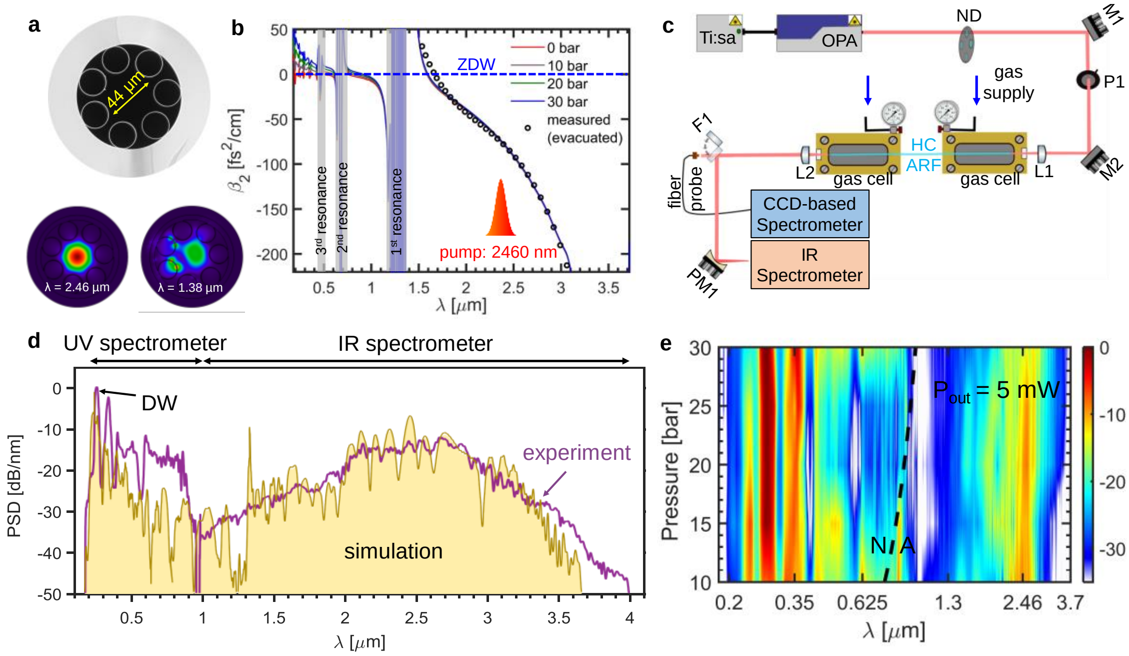

Figure 1. (a) Scanning Electron Microscope (SEM) image of the fabricated HC-ARF and the mode profiles at the pump and resonance wavelengths. (b) Calculated resonances (horizontal bars) and GVD for the HC-ARF at different pressures of the Ar-gas (solid lines) together with the measured dispersion of the evacuated fiber in the mid-IR for comparison (circles). (c) Experimental setup used for SC generation: Neutral density filter (ND) and linear film polarizer (P1) are used to control the input power, protected silver mirrors (M1-3), CaF_2 plano-convex lenses (L1-2), flip mirror (F1), and a gold coated parabolic mirror (PM1). (d) Simulated and measured SC spectrum of the 30 bar Ar-filled hollow core fiber, pumped at 2460 nm with ~8 μJ injected pulse energy. (e) Measurement of the pressure-dependent SC spectrum at a fixed output power of 5 mW, corresponding to ~8 μJ injected pulse energy.

In conclusion, we have experimentally demonstrated record multi-octave SC generation from DUV to mid-IR using a single gas-filled HC-ARF driven by ultrashort mid-IR pump pulses at 2460 nm. This report constitutes a significant step towards bridging the gap between DUV and the molecular fingerprint mid-IR region for novel spectroscopic applications.

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