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Ultrafast fiber laser for high-harmonic generation in solids

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SUMMARY

We report on high harmonic generation in a Zinc oxide bulk sample driven by a fiber laser system. The laser delivers 50 fs pulses with 0.92 μJ at 1.55 μm , leading to the generation of harmonics up to H7. To our knowledge, this is the first solid-state HHG source driven by a high-energy few-cycle fiber laser in the telecommunication region.

KEYWORDS: *High harmonic generation, pulse self-compression, fiber laser, hollow core fibers*

1. INTRODUCTION

High-harmonic generation (HHG) is a nonlinear optical process resulting from the interaction of a strong laser field with an atom, a molecule, or a plasma. In this phenomenon, the target system emits light at frequencies equal to integer multiples of the frequency of the driving laser [^{1,2,3}]. HHG is a promising research area from both fundamental and practical points of view and have enabled the generation of coherent extreme-ultraviolet radiation that has pioneered numerous applications. Solid-state HHG has gained attention for its potential to control and customize radiation properties. In solids, the mechanism involves inter- and intraband electronic dynamics, resulting in brighter and more intense HHG compared to gases. The coupling between electrons and holes allows excited electrons to recombine in neighboring sites, strengthening the HHG spectrum [³]. Additionally, it offers more degrees of freedom to act on the HHG emission by engineering the crystal structure, chemically or mechanically [⁴⁻⁷]. HHG strongly depends on the driving wavelength: while in gases the high harmonic cut-off depends on the square of the driving wavelength strength, it depends linearly on the field strength for solids [^{8,9}]. The use of long wavelength pulses (Mid IR) extends the cut-off and increases damage threshold of bulk crystals [³]. This has been achieved using high power optical parametric chirped pulse amplifiers (OPCPA) [^{3,10-12}] and optical parametric amplifiers (OPA) [¹³⁻¹⁷]. These systems offer high energy levels but they present very complex configurations and in general operate at low repetition rates.

The use of ultrafast fiber lasers in the mid-IR is a very promising route for the development of ultra-compact HHG platforms. This has been confirmed by several demonstrations of HHG driven by few-cycle mid-IR fiber lasers [^{7,18}]. However, these sources based on soliton self-frequency shift in

all-solid fibers are limited to few-10 nJ [7,18]. The best solution for obtaining high energy levels in a fibered configuration involves the use of post-compression in hollow core (HC) photonic crystal fibers (PCF) filled with rare gases. Such fibers provided the best self-compression qualities due to their high nonlinearity versus ionization rate ratio and do not exhibit any delayed Raman response compared to traditional pulse compression methods, as they use an atomic gas. Moreover, the dispersion of the waveguide is an additional degree of freedom for pulse propagation tailoring. Working in the anomalous dispersion regime indeed offers the possibility to generate Fourier limited pulse directly from the fiber, due to the interplay between self-phase-modulation-induced spectral broadening and simultaneous temporal compression due to the anomalous waveguide dispersion [19].

2. EXPERIMENTAL SETUP AND RESULTS

The schematic diagram of our HHG laser system is depicted in Fig. 1. The laser source is based on nonlinear pulse compression in a HC-PCF filled with gas and pumped by an erbium-doped fiber chirped-pulse amplifier system delivering sub-picosecond pulses with 600 fs duration and up to 3 μJ energy at 660 kHz repetition rate. The elliptically polarized beam is injected into the post compression stage based on a 2 m long hybrid Kagome HC-PCF (33 μm diameter, $\beta_2 -6300 \text{ fs}^2/\text{m}$ @ 1550 nm) [20] filled with argon. We use a three lenses scheme to adapt the beam size and optimize the injection efficiency. The collimated beam at the output of the HC-PCF passes through a half wave plate ($\lambda/2$) and a thin film polarizer (TFP) that is used in combination with the waveplates before the HC-PCF to temporally purify the output beam from any residual light propagating in high-order modes and thus to enhance the output pulse contrast.

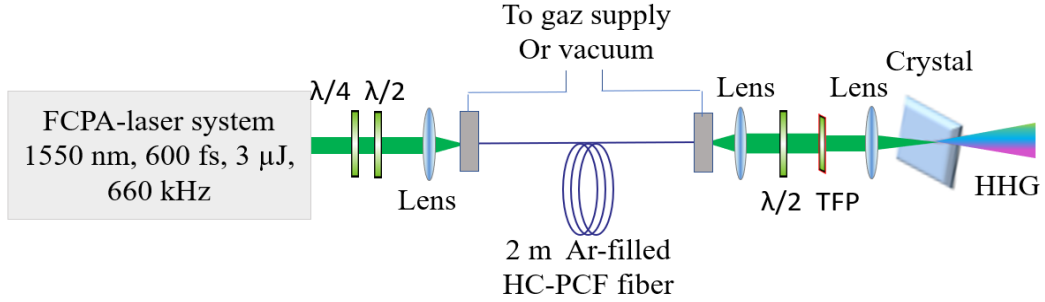


Figure 1: Schematic diagram of the sub-50 fs fiber laser system driving HHG in solids.

In our setup, pulse self-compression is reached for a gas pressure of 13 bar and an input energy of 2.5 μJ with 600 fs pulses. At the HC-PCF output, we achieved strongly SPM-broadened spectra spanning from 1412 nm to 1675 nm as shown in Fig. 2.a. The corresponding autocorrelation trace shown in the inset reveals a FWHM pulse duration of 50 fs, assuming a Gaussian shape. The output energy after polarization filtering is 0.92 μJ . To explore HHG, the post-compressed pulses were focused onto a 500 μm thick ZnO sample (spot size of 20 μm), and the intensity in the focus was estimated to 5.8 TW/cm^2 . HHG spectra measured using an Ocean Optics (*Maya 2000 pro*, 200 nm-1200 nm) spectrometer reveal the generation of perturbative and non-perturbative harmonics extending well above the band gap ($\Delta E=3.3 \text{ eV}$) and luminescence generated at the excitonic band edge centered at 385 nm.

In this experiment, we were limited to the measurement of H7 (seventh harmonic) due to our detection system but the current experimental setup will be shortly updated in order to measure higher harmonics in XUV. This will be discussed during the conference.

3. CONCLUSION

In this communication, we present a high-energy ultrafast fiber laser delivering few cycle pulses in the telecommunication region and demonstrate its use for HHG in ZnO bulk crystals. The

source is based on a nonlinear pulse self-compression process occurring in a gas-filled hollow core fiber and enabling the generation of 50 fs pulses with 0.92 μJ at 1.55 μm .

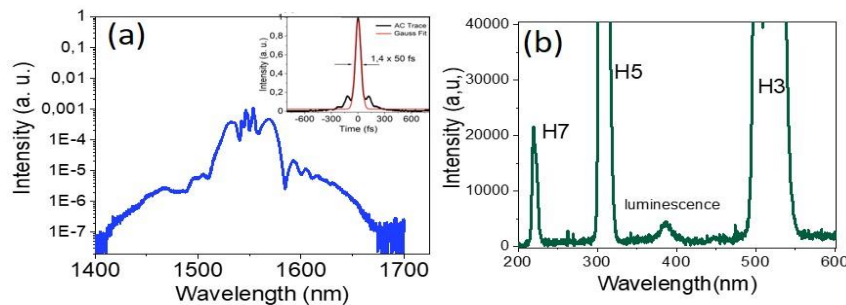


Figure 2 : Experimental results. (a) Output laser characteristics: optical spectrum and autocorrelation trace (inset), (b) Harmonic spectrum emitted by the ZnO crystal.

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