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# High energy 50 fs fiber-based laser system for high harmonics generation in solids

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**Abstract.** We report on a high energy ultrafast fibre laser architecture designed for high harmonics generation in solids. The laser delivering 50 fs pulses with 2.12  $\mu\text{J}$  at 1550 nm has enabled the generation of harmonics up to harmonic H5 from a magnesium oxide (MgO) bulk sample. To the best of our knowledge this is the first solid-state HHG source driven by a  $\mu\text{J}$ -class few-cycle fiber laser in the mid-IR region.

## INTRODUCTION

Since their first demonstration [1], high harmonics generation (HHG) in solids has become a hot topic for ultrafast science. It offers new possibilities for building compact ultrafast light sources in the extreme ultraviolet (EUV). These EUV sources offer a considerable potential to push the current limits of various applications, such as high-resolution spectroscopy, lithography and tomography.

HHG is typically achieved by strongly focusing an intense infrared (IR) driving pulse into the solid, generating odd-order harmonics of the fundamental frequency. It is explained by the electronic dynamics implying electron oscillation in the conduction band (intraband acceleration) and interband coupling between the valence band and the conduction band (interband tunnelling and recombination) [1]. These two processes are strongly coupled and their relative importance depends on the experimental parameters (material type and driving wavelength) [1].

The major breakthrough has occurred in 2011 with the demonstration of low threshold HHG in a ZnO crystal using few-cycle mid-IR pulses [2]. The use of long wavelength pulses improved the HHG efficiency and increased damage threshold of bulk crystals. This was achieved using high power optical parametric chirped pulse amplifiers (OPCPA) [2-5] and optical parametric amplification (OPA) [6-10]. However, these systems are complex and require optical synchronization in the

generation process. Given the relatively low threshold of HHG in solids, the use of ultrafast fibre 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 [10-11]. However, these sources based on soliton self-frequency shift in all-solid fibers are limited to few-10 nJ [10-11].

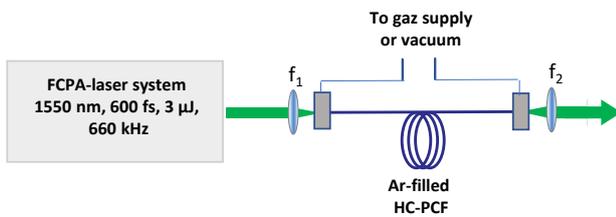
In this contribution, we demonstrate a high-energy fiber-based laser architecture operating around 1550 nm. Using a nonlinear pulse compression stage based on a hollow-core photonic crystal fiber (HC-PCF) filled with noble gases pumped by high-energy sub-picosecond pulses, we demonstrate the generation of sub-50 fs pulses with more than 2  $\mu\text{J}$  at 660 kHz repetition rate. Preliminary results show that the laser performances are very suitable for HHG in solid materials.

## Experimental Setup and results:

The schematic diagram of our laser system is depicted in **Fig. 1**. It consists in an erbium-doped fiber chirped-pulse amplifier system delivering sub-picosecond pulses with 600 fs duration and up to 3  $\mu\text{J}$  energy at 660 kHz repetition rate. The linearly polarized laser beam centered at 1550 nm is injected into the post-compression stage based on a kagome-type HC-PCF with 33  $\mu\text{m}$  core diameter. We use a three lenses scheme to adapt the beam size and optimize the injection efficiency. The 2 m-long HC-PCF is held in a gas cell and filled with argon at different pressures. The transmission efficiency through the fiber assembly is

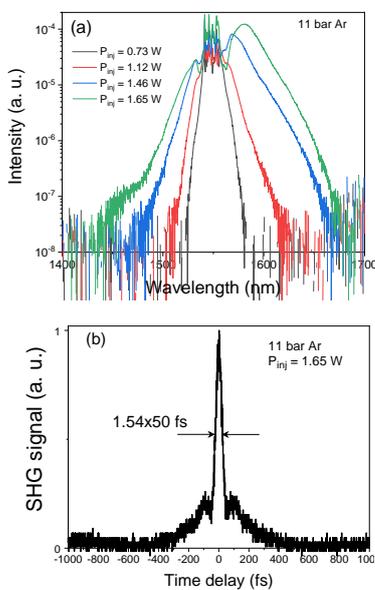
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higher than 85 %. Compared to traditional pulse compression methods based on solid-core optical fibers of bulk materials, hollow-core fibers allow single mode guidance on larger mode sizes and, hence, are suitable for larger pulse energies. Also, the use of noble gases offers the possibility to control the nonlinearity strength by changing the gas type and pressure. Moreover, the dispersion of the waveguide is an additional degree of freedom for pulse propagation tailoring. Indeed, the fibre used in our experiments exhibits an anomalous dispersion above  $1.3 \mu\text{m}$  with about  $-6300 \text{ fs}^2/\text{m}$  at  $1550$ . This propagation regime is favorable for pulse self-compression based on shock-wave formation in the HC-PCF [13].



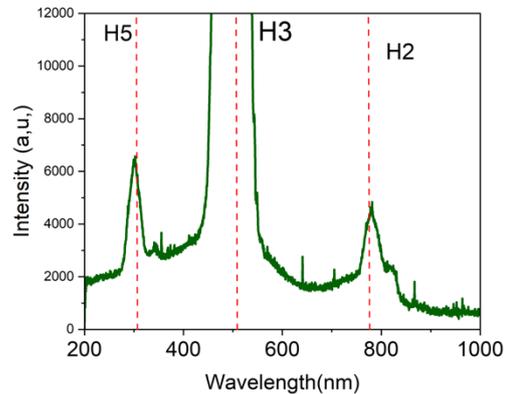
**Fig. 1.** Schematic diagram of the sub-50 fs fiber laser system.

Pulse self-compression is reached for a gaz pressure of 11 bar and an input energy of  $2.5 \mu\text{J}$  ( $1.65\text{W}$  average power) with 600 fs pulses. The optical spectra measured at different injected power levels are shown in **Fig. 2(a)**. As expected a strong spectral broadening is observed with increasing pulse energy before reaching the self-compression regime characterized by a typical asymmetric spectral shape. The pulse duration inferred from the autocorrelation trace assuming a secant hyperbolic shape is  $\sim 50$  fs, see **Fig 2(b)**. The corresponding output pulse peak-power is  $\sim 42 \text{ MW}$ .



**Fig. 2.** Laser outputs: Optical spectra for different injected powers (a) and autocorrelation trace of the self-compressed pulses (b).

The compressed pulses were then focused into a  $200 \mu\text{m}$ -thick MgO sample to explore HHG. The harmonics signal is observed and optimized by moving the sample on a translation stage along the optical axis. The spectral analysis of the transmitted beam reveals the generation of all odd harmonics up to H5 as shown in **Fig. 3**. In this experiment, we were limited to the measurement of H5 due to our detection system. More work is needed to optimize the detection setup and to explore other materials. This will be discussed during the conference.



**Fig. 3.** Spectra emitted from MgO crystal using Ocean Optics (Maya 2000 pro) (200 nm-1200 nm)

In conclusion, we have presented a high-energy ultrafast fiber-based source particularly adapted for high harmonic generation in solids. The source is based on a nonlinear pulse self-compression process occurring in a gaz-filled hollow core fiber and enabling the generation of 50 fs pulses with  $2.12 \mu\text{J}$  at  $1.55\mu\text{m}$ .

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