Title
Globally Optimized Monochromator for Coherent Diffractive Imaging with Tunable EUV Wavelength

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High Performance Compression of 515 nm Laser Pulses at kHz-MHz Repetition Rates for Ultrabright EUV High Harmonic Generation

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Abstract: We demonstrate a single-stage multi-plate compression of 515 nm second harmonic pulses of Yb:KGW laser amplifier from 180 fs to 40 fs, ideal for efficient EUV high-harmonic generation using 0.1-1 MHz visible driving lasers. © 2022 The Author(s)

Observing the ultrafast dynamics of the atomic, molecular, and nanomaterial world requires coherent sources with ultrashort wavelength and ultrashort pulse duration. EUV sources based on the process of high harmonic generation have gained their status quo in the field through upconversion of near-IR pulses from Ti:Sapphire, OPA, and OPCPA ultrafast light with high energy and high peak power. Here we demonstrate the capability of a kHz-MHz Yb:KGW sub-picosecond amplifier at 1030 nm to be utilized for high efficiency high harmonic generation in the EUV region by spectrally broadening and subsequently compressing its second harmonic at 515 nm. The advantages of high harmonic generation in gases driven by short-wavelength VIS lasers are extremely high single-atom efficiency due to low quantum diffusion of the rescattering electron, ultra-narrow linewidths of the harmonics due to broader temporal phase-matching window, enhanced phase and group-delay matching due to high linear and nonlinear indices of refraction of atoms and ions [1, 2]. In addition, the superb spatial coherence, and finally, an extended X-ray cutoff with intrinsically-compressed near-transform limited attosecond pulses makes this technique very attractive for high-resolution dynamic imaging and for angle-resolved photoemission spectroscopies [1].

Many successful approaches have been demonstrated to date where femtosecond pulses at the fundamental laser wavelengths of Ti:Sapphire-based or Ytterbium-based lasers or optical parametric amplifiers of 800 nm and 1030 nm have been compressed to few cycles in duration [3, 4]. However, a practical compression of spectrally broadened UV-VIS laser pulses at high average power has not been utilized. In this work, we demonstrate a near spatio-temporal solitary-mode of propagation in periodic thin-plate media at VIS laser wavelengths and achieve spectral broadening via self-phase modulation while maintaining an extremely good spatial profile of nearly-identical spot sizes and similar pulse durations at each plate. This eliminates the strong conical emission and enhances the efficiency of the pulse broadening geometry to above 93%, resulting in a compression from 180 fs to 40 fs at 515 nm, or ~23 cycles at FWHM. This pulse duration is in the optimal range for effective phase matching of high order harmonic generation using UV-VIS drivers.

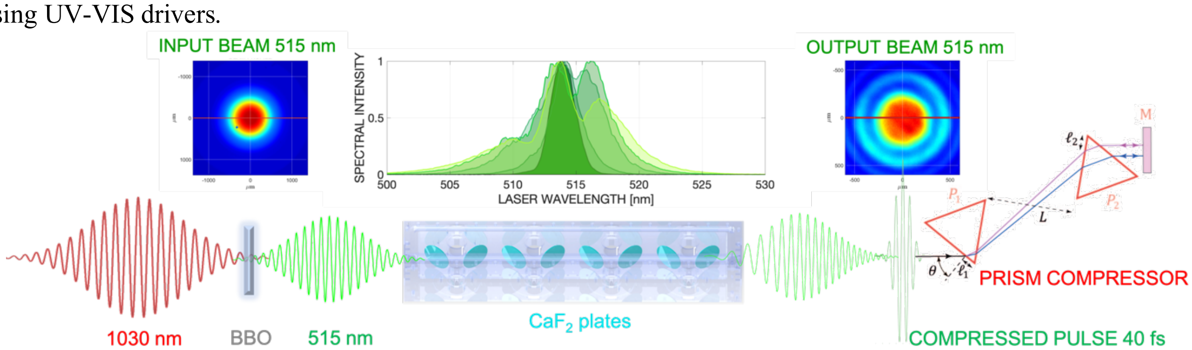

Figure 1. Spectral broadening and compression of ultrafast VIS 515 nm laser pulses. Experimental setup: 250 fs, 1030 nm near-IR laser pulses from a KGW laser amplifier are upconverted to 180 fs, 515 nm pulses in a BBO crystal. The VIS pulses are spectrally broadened in an array of thin CaF_2 plates with a 93% efficiency, then compressed using a prism-pair compressor to 40 fs in an excellent beam with 93% of the energy in the central spot, and with overall combined efficiency of 75%. The spectral broadening of the VIS pulses supports a 35 fs transform-limited pulse duration.

In our experiments, a Yb:KGW laser amplifier of 8 W average power, with a tunable repetition rate between 95 kHz and 1 MHz, and 250 fs pulse duration, is used to generate second harmonic pulses in a Type I BBO crystal with a high conversion efficiency of >67%. The 515 nm beam of 56 μJ energy per pulse (at 95 kHz) and 180 fs pulse duration is then focused by a long focal length lens of F=1 m, ensuring a long Rayleigh range of interaction. Eight CaF_2 thin plates of 1 mm thickness, equally spaced by 2 inches, are used as a nonlinear material for spectral broadening, with the first plate placed right at the flat wavefront of the beam in the focus. The plates are arranged in a vacuum chamber in a simple counter-rotating configuration at a Brewster angle of incidence to reduce surface reflections, to minimize any wavefront distortions, and to eliminate gas-induced nonlinearity. Less than 7% are lost after 16 reflecting surfaces. The pulses are compressed by an optimized UV-grade fused-silica prism-pair compressor with a prism separation of L = 40 cm. In an optimized geometry, the measured beam profiles and the pulse durations remain nearly the same at each plate, with a very weak conical emission ring at the output with below 7% of the energy localized in the rings (see Fig. 1). The overall losses through the SPM system and the prism-pair compressor account for 75% throughput or an energy of ~ 42 μJ. We achieve compression to a pulse duration of 40 fs, measured using a second-harmonic generation FROG and a self-diffraction FROG (Fig. 2), for a spectral broadening supporting a transform-limited pulse of ~35 fs. We developed analytical perturbative high-order dispersion formalism to characterize prism-pair and chirped mirror compressors up to the 10^{th} order of dispersion for the VIS 515 nm wavelength range to minimize further any losses (Fig. 2).

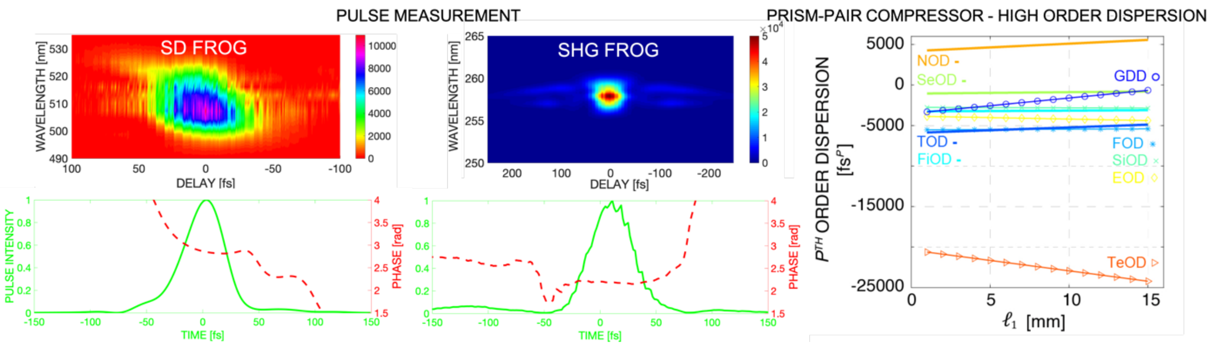

Figure 2. Left: Pulse measurements - experimental traces from SD and SHG FROGs and the corresponding retrieved 515 nm pulse intensity in the time domain. Right: Dispersion compensation calculation for a prism-pair compressor at various insertion distances up to the 10^{Th} dispersion order.

Phase matching of high harmonic generation using UV-VIS drivers favors longer pulse durations since the temporal phase-matching window for efficient upconversion in the EUV – X-ray regime increases with the decrease of the laser wavelength [1, 2]. The demonstrated straightforward compression scheme provides a driver of a 23-cycle pulse duration and a feasible peak intensity of >1.0×10^{15} W/cm^2 to reach the soft X-ray regime at ~100 eV at repetition rates of 100 kHz and higher, i.e. more than 2 orders of magnitude greater compared to that of the most common laser amplifiers. Theoretically, the emission can reach the technologically relevant 13.5 nm EUV wavelength with very narrow linewidths using Ar ions and neutral He (see Fig. 3).

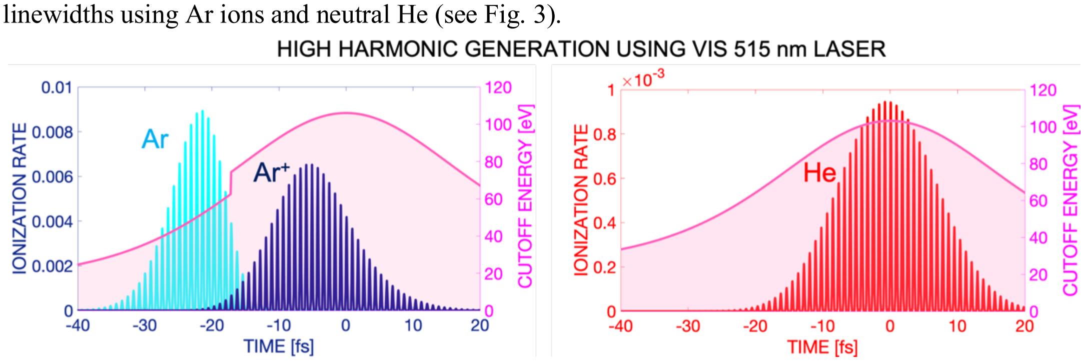

Figure 3. Theoretical high harmonic cutoffs at the technologically relevant 13.5 nm EUV wavelength (91.7 eV) for a 515 nm driver with a 40 fs pulse duration for an experimentally feasible peak intensity of 1.0×10^{15} W/cm^2 (ionization of Ar ions in blue and neutral He gas in red).

In summary, this work demonstrates a simple and straightforward way to obtain short 40 fs VIS pulses at the second harmonic wavelength of sub-picosecond kHz-to-MHz Yb-based laser amplifiers. The very high-quality spatial profile and great power efficiency makes this single-stage scheme an attractive frontend for ultrabright high harmonic generation using VIS driving lasers.

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