Efficiency Scaling of High Harmonic Generation driven by a tunable Optical Parametric Amplifier in the Visible

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Abstract: High Harmonic Generation efficiency increases for short driver wavelengths. We study experimentally the driver wavelength dependence around 32 eV by driving the process with a tunable Optical Parametric Amplifier in the visible range.
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1. Introduction

High Harmonic Generation (HHG) is an optical technique allowing for the production of photons in the Extreme UV (EUV), soft and hard X-ray regions, obtained by focusing an ultraviolet, visible or infrared femtosecond pulse, called driver, in a material, typically a noble gas. HHG efficiency and cutoff extension have a strong dependence on the wavelength of the driver pulse. In this work we demonstrate a high energy tunable Optical Parametric Amplifier (OPA) in the visible range. With this source we generate HHG in Argon, study the wavelength dependency of the energy conversion efficiency for single harmonics, and find good agreement with a previously developed theory.

2. Tunable OPA in the visible

The OPA used is based on the work in reference [1]. The setup is shown in Fig. 1. We start from a commercial amplified Ti:sapphire laser emitting 6 mJ, 35-fs pulses at 800 nm with a 1-kHz repetition rate. The amplifier output energy is split into three parts. 1% of the pulse energy is used to generate a seed in the visible range by white light continuum generation in a 2-mm-long sapphire plate. 9% of the energy is frequency doubled in a 0.5-mm long β-Barium Borate (BBO) crystal, generating a 40 μJ pump at 400 nm used to amplify the visible seed up to 4 μJ in a 1-mm-long BBO crystal. A SF10 prism compressor, with 7-cm apex distance, is used to compensate for the dispersion induced by the materials crossed. The remaining 90% of the amplifier output energy is frequency doubled and generates 2 mJ pulses at 400 nm. These pulses are used as a pump for the second and third OPA stages. The first OPA stage energy is amplified to around 15-20 μJ in a 1-mm-long BBO crystal (second OPA stage), and the output is amplified in the third stage up to 200 μJ. To improve the wavefront matching, we tilt the pump wavefront with a CaF_2 prism.

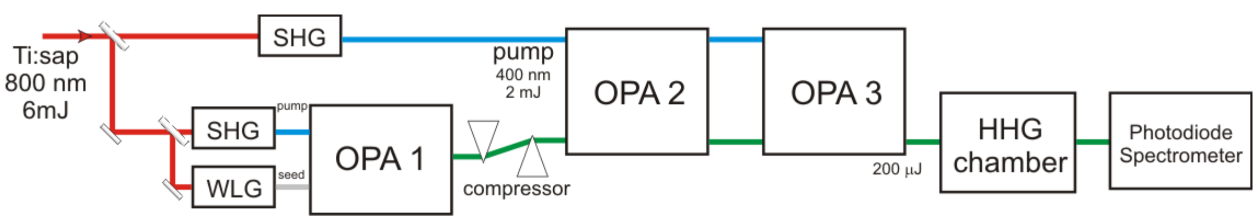

Fig. 1: schematic of the experimental setup.

The OPA shows a broad tunability in the visible range, from 500 nm to 630 nm. We characterized the OPA output duration by self diffraction background free autocorrelation, and the Full Width at Half Maximum (FWHM) duration is between 34 and 39 fs. Pulses shorter than 6 fs could be obtained by using a double chirped mirror compressor instead of a prism compressor [2].The pulse-to-pulse energy stability is 2.54% rms, measured over 9 minutes. The OPA shows very good noise performances, with a superfluorescence level below 0.5% of the signal energy. The beam M^2 is 1.9.

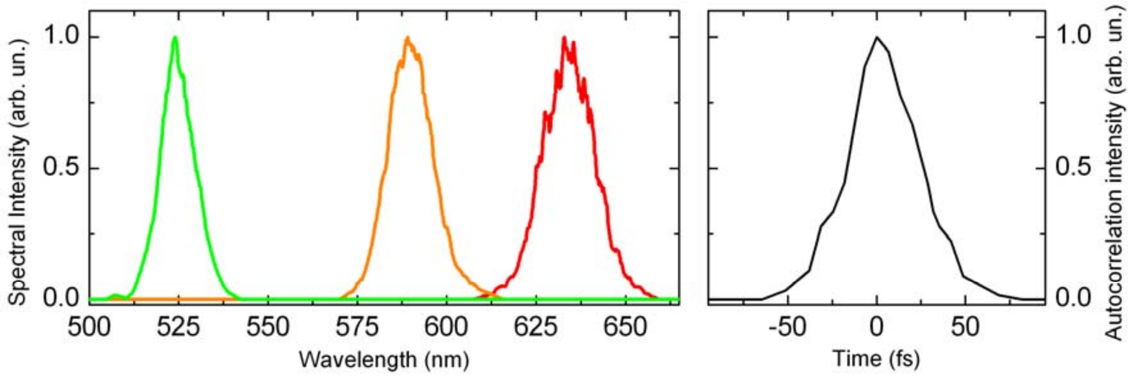

Fig. 2: Spectra and autocorrelation of the visible OPA. The spectra shown were used to drive the HHG experiment. The autocorrelation is relative to the 590 nm pulse and corresponds to 34 fs FWHM pulse duration.

3. HHG in Argon

We used the OPA to drive HHG in an Argon gas jet, with a 40 mbar pressure (500 mbar backing pressure), and measure the efficiency around 32 eV. We drive HHG with 3 wavelengths generated by the OPA, namely 524 nm, 589 nm and 633 nm, and with the fundamental and second harmonic frequencies of the laser source, i.e. 800 nm and 400 nm. The spectra of the OPA and one of the autocorrelations are shown in Fig. 2. We measure the beam size in the focal position with the knife edge method and keep similar intensities for all 5 driver wavelengths. Table 1 summarizes the characteristics of the 5 driver pulses.

Table 1: Characteristics of the driver pulses used for the HHG wavelength scaling study.

Driver wavelength (nm)	Duration FWHM (fs)	Size at focus (µm x µm)	Energy (µJ)	Intensity (x 10^{14} W/cm^2)
400	26	26x26	85	3.1
524	39	33x23	82	1.8
589	34	34x17	85	2.8
633	36	31x18	82	2.6
800	35	21x21	85	3.5

Fig. 3 shows the EUV spectra obtained in the 5 experiments for the indicated driver wavelengths. In the 400-nm case the signal is much higher than in the other cases, so the peak is not shown. The "*" symbol shows the photon count number that has been considered for the wavelength study.

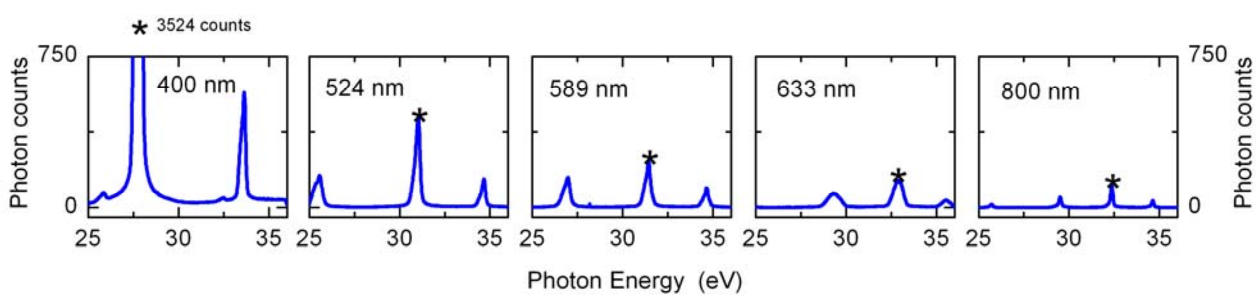

Fig. 3: HHG spectra for the 5 different wavelengths of the efficiency study (linear scale).

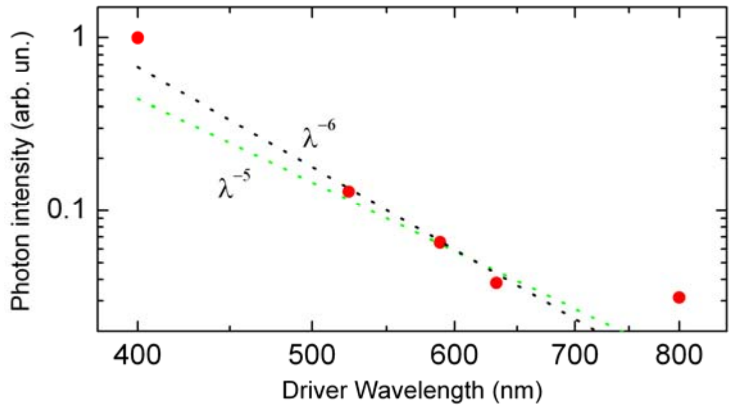

Fig. 4: Efficiency scaling in Argon vs. visible driver wavelength. (Red: experimental data). Black and green dots: theoretical predictions).

Fig. 4 shows the normalized number of photon counts observed in the spectrometer. As expected, the efficiency decreases as the wavelength increases. The result fits very well with the theoretical predictions, presented for example in [3], or [4], where an efficiency scaling of $\lambda^{-5} \div \lambda^{-6}$ is predicted. While the 3 experimental points observed with the OPA fit very well with the theoretical models, the two points at the fundamental frequency and at the second harmonic of the laser show a slightly higher efficiency. This might be due to the better beam quality in the laser beam than in the OPA, and also to their higher intensity, as indicated in Table 1.

4. Conclusion

In conclusion, we developed a tunable, high energy OPA in the visible range, starting from an amplified Ti:sapphire system with a 1-kHz repetition rate. We generate EUV pulses by driving HHG in Argon and, due to the broad tunability of our OPA, we are able to confirm efficiency scaling vs. driver wavelength in the visible wavelength range, thus experimentally verifying the theoretical predictions.

Other tunable sources like OPAs can be used to verify the driver wavelength dependence of HHG characteristics, like conversion efficiency and cutoff energy.

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