Recent advances in scaling the power of extreme ultraviolet frequency combs

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Abstract: High-temperature gas-mixtures increase gas-jet velocity and reduce plasma accumulation, leading to phase-matched high-harmonic generation. A noncollinear intracavity geometry provides high outcoupling efficiency. We outcouple a record power of 600μW at 97nm with 60% outcoupling efficiency.

Infrared laser-driven high harmonic generation (HHG) in gases is a well-established method for generating coherent XUV radiation. It is typically achieved using low repetition rate (<100 kHz) laser systems. However, many applications require high repetition rates, e.g., for high counting statistics. Most notably, frequency stabilization for precision XUV frequency comb spectroscopy requires repetition rates >>10 MHz. Our work addresses two leading challenges in power-scaling of high repetition rate HHG: Phase-matching and cavity outcoupling.

Phase matching: Efficient HHG requires matching the phase velocities of the driving infrared wave and the generated XUV wave. XUV radiation is then generated in-phase along the generation gas and adds up constructively. This is known as phase-matching. When the repetition rate exceeds ~10 MHz, phase-matching becomes very challenging. The reason is that the high laser intensities required for HHG (~10^{14} W/cm^2) result in plasma generation. At high repetition rates the plasma generated by one pulse does not have time to clear the generation volume before the next pulse arrives and generates more plasma. Therefore, a high-density steady-state accumulation of plasma is formed in the generation volume. This plasma is highly dispersive and prevents phase-matching, leading to low HHG efficiency. In our system, the generated power was just ~200 μW per harmonic.

We address the steady-state plasma problem by adding a light carrier gas (helium) to the heavy generation gas (xenon). Also, we heat up the gas to ~550°C. Both actions contribute to increasing the gas jet forward velocity, thus reducing the number of consecutive laser pulses that interact with the same atom/ion.

Our XUV comb system consists of a 80 W, 77 MHz repetition-rate Yb:fiber frequency comb at a wavelength of 1070 nm, locked to a passive enhancement cavity. Using a 9:1 He:Xe gas mixture, with a backing pressure of ~100 bar applied to a heated quartz nozzle, we were able to generate ~2 mW and ~0.9 mW at 97 nm and 67 nm, respectively [1].

Outcoupling: High repetition rate HHG is carried out in enhancement cavities, which stack laser pulses in order to reach the intensity required for HHG. Coupling the generated XUV light out of the cavity efficiently is challenging, since there are no suitable XUV optics.

Past approaches achieved outcoupling efficiency of ~10%. In some cases, outcoupling dispersed the beam, so that different harmonic orders propagate in different directions. While useful for spectroscopy, this approach does not allow outcoupling of attosecond pulses.

We used a non-collinear enhancement cavity (Fig. 1), where intracavity beams cross at the focus. This leads to XUV emission along the bisector of the crossing beams. Since the XUV beam is not collinear with the infrared beam, it can be efficiently outcoupled by simply propagating through a gap between cavity mirrors.

By combining the two methods described above, at a repetition rate of 154 MHz, we achieved a record-high out-coupled power of 600 μW in a single harmonic at a wavelength of 97 nm. This corresponds to a >60% out-coupling efficiency [2].

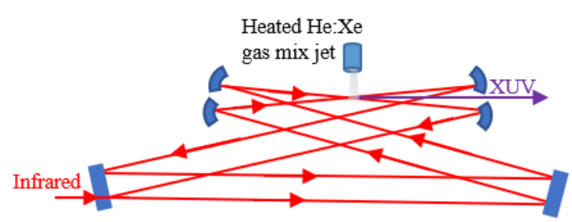

Fig. 1. Phase-matched high-repetition-rate HHG in a non-collinear enhancement cavity.

References

[1] G. Porat et al., Nature Photonics 12, 387 (2018).

[2] C. Zhang et al., Phys. Rev Lett. 125, 093902 (2020).