Boosting the Efficiency of Attosecond Pulse Amplification via the Mutual Scattering of High Harmonics in Optically Dressed Hydrogen-Like Plasma-Based X-Ray Laser

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From the end of the 20th to the beginning of the 21st century, a new interdisciplinary field of research, called attosecond physics, has been arose and began rapidly developing due to the development of the sources of attosecond extreme ultraviolet (XUV)/X-ray pulses based on the high-order harmonic generation (HHG) of intense optical/infrared (IR) laser fields in gases in the tunnel ionization regime. Nowadays, the pulses generated by such sources can be as short as 40-50 as. However, the corresponding pulse energy in the X-ray range does not exceed a few nJ (mainly because of the macroscopic pulse propagation effects), which limits their practical applications, for example, in the single-shot measurements of ultrafast process, as well as in the initiation and study of nonlinear processes in the XUV/X-ray range. Thus, enhancing the energy of high harmonics (HHs) and attosecond pulses is an important task both fundamentally and practically.

Recently, it has been shown that a set of HHs can be amplified as a whole in an active medium of a hydrogen-like plasma-based X-ray laser, which is simultaneously irradiated by a replica of the laser field used to generate the harmonics [1]. The laser field leads to the splitting and sub-laser-cycle linear Stark shift of the excited energy levels of the resonant ions. As a result, the gain of the active medium is redistributed from the single frequency of the resonance to the multiple combinational frequencies, which coincide with the frequencies of HHs. It was shown that in a plasma with high electron density and strong dispersion near the frequency of the modulating laser field, the HHs are amplified independently of each other so that their relative phases are maintained during the amplification process. Together with the ability to achieve approximately the same gain coefficients for the HHs *via* a proper choice of the intensity of the modulating field, this allows for the amplification of attosecond pulse trains with approximate preservation of the duration and shape of the pulses.

In the present contribution, we generalize this method to the case of the active medium of an X-ray laser with comparably low free-electron density and moderate dispersion for the modulating field. In this case, each HH is not only amplified but also generates the coherently scattered fields at the frequencies of the other harmonics. It is shown that the maximization of the coherently scattered fields and their synchronization with the radiation of the amplified HHs *via* the proper choice of the medium length, as well as intensity and wavelength of the modulating laser field, and the sub-laser-cycle delay of the HH field relative to the laser radiation makes it possible to increase the intensity of the attosecond pulses at the output from the medium by several times with respect to the active medium with high electron density. The possibilities for experimental implementation are discussed for the hydrogen-like Li^{2+} X-ray laser with an inverted transition wavelength of 13.5 nm.

References

[1] V A Antonov, K Ch Han, T R Akhmedzhanov, M Scully and O. Kocharovskaya, Phys. Rev. Lett. **123**, 243903 (2019)