Mutual amplification of high-order harmonics for increasing efficiency of sub-femtosecond pulse train amplification in optically dressed plasma-based X-ray laser

Vladimir Antonov[1,2,*], Ilias Khairulin[1], Mikhail Ryabikin[1,2], and Olga Kocharovskaya[3]

[1]Institute of Applied Physics of the RussianAcademy of Sciences,
46 Ulyanov Street, Nizhny Novgorod 603950, Russia

[2]Prokhorov General Physics Institute of the RussianAcademy of Sciences,
38 Vavilov Street, Moscow 119991, Russia

[3]Department of Physics and Astronomy, TexasA&MUniversity,
College Station, 578 University Drive, Texas77843-4242, USA

*email: antonov@appl.sci-nnov.ru

Recently, it has been shown that a set of high-order harmonics (HHs) of an optical / infrared laser field can be amplified 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 amplification becomes possible due to the redistribution of the gain of the active medium from the single frequency of the resonance to the multiple combinational frequencies, which coincide with the frequencies of HHs. This gain redistribution occurs due to the sub-laser-cycle Stark shift of the excited energy levels of the resonant ions under the action of the laser field. 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. In this case, their relative phases are maintained during the amplification process. Together with the possibility to achieve approximately the same gain coefficients for the harmonics of different orders via a proper choice of the intensity of the modulating field, it allows for the amplification of attosecond pulse trains.

In the present contribution, we consider the active medium of an X-ray laser with low density of free electrons and thus moderate dispersion for the modulating field. We show that in this case the efficiency of HH amplification can be considerably increased with respect to the case of a dense plasma medium with the same unperturbed gain coefficient. The efficiency of HH amplification increases due to the constructive interference of the amplified HH field with the coherently scattered fields, which are generated by each harmonic at the frequencies of the other harmonics in the plasma with low electron density. We call this effect "mutual amplification of high-order harmonics" (MAHHs). It can be observed at specific lengths of the active medium, for certain intensities of the modulating field and sub-laser-cycle delays of the HH field relative to the laser radiation. It is shown that MAHHs might allow to increase the intensity of the amplified sub-femtosecond pulse trains up to an order of magnitude as compared to the dense plasma medium. Moreover, under the conditions of MAHHs it is possible to control the relative amplitudes and phases of the harmonics of different orders [2]. The possibilities for experimental implementation are discussed for the case of Li^{2+} active medium of an X-ray laser at 13.5 nm wavelength.

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

[2] I. R. Khairulin, V. A. Antonov, O.A. Kocharovskaya, *Quantum Electronics*,**2020**, 50, 375-385.