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Super-high frequency upshifting in the nonlinear interaction of laser pulse with breaking wake wave

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The generation of coherent high-frequency radiation is the topic of great interest since the invention of lasers. Among the proposed schemes are the x-ray laser, free-electron laser, high-order harmonic generation in gases, relativistic harmonics from the solid targets, and so on. Recently, the relativistic frequency upshifting accompanied by the light intensification and pulse shortening was proposed using the Flying Mirror technique [1]. According to the relativity theory, the frequency of light pulse reflected at the relativistic mirror moving toward it, is upshifted by the factor $\approx 4\gamma^2$. Here we describe new method of super-high frequency generation, using simultaneously the relativistic upshifting and harmonic generation, resulting in the net factor of $4N\gamma^2$, where N is the harmonic number.

When a relativistic-irradiance laser pulse ("driver", subscript "0") propagates in the underdense plasma, it creates a wake wave with the phase velocity equal to the group velocity of the driver pulse, which is close to the velocity of light c for a small plasma density n_0. The gamma-factor is $\gamma \approx \omega_0/\omega_{pe} >> 1$, where ω_0 is the driver pulse frequency, $\omega_{pe} = (4\pi n_0 e^2/m)^{1/2}$ is the Langmuir frequency, and e and m are the electron charge and mass. At or near the wave breaking condition, the electron density profile in the wake wave has cusps with the peak density much higher than the unperturbed plasma density. The electrons within the cusps move with the velocity close to the phase velocity of the wake wave. Counter-propagating source pulse (subscript "s") is partially reflected from the cusps. If the source pulse is substantially strong, the reflected pulse contains not only the upshifted fundamental frequency $4\gamma^2\omega_s$, but also harmonics. This nonlinear reflection leads to the spectrum containing components with the frequencies equal to $4N\gamma^2\omega_s$. Even for moderate values of γ and N, the source pulse frequency can be upshifted hundreds or thousands times. Furthermore, the gamma-factor is relatively easy to control via the plasma density, which gives rise to the tunable source of high-frequency pulses. In the time domain, the reflected pulse duration shrinks approximately by the factor $4\gamma^2$ compared to the source pulse. Selecting several harmonics by a spectral filter, even shorter pulses are possible to produce.

We developed an analytical model of the super-high frequency upshifting based on the model developed for the laser – thin-foil interaction [2 - 4]. We also addressed the range of laser and plasma parameters for which the model is applicable.

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