Generation of few-cycle electromagnetic pulses at combination frequencies of two-color ionizing laser field

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Synopsis The ionization-induced wave mixing is studied analytically and numerically as a new way for the efficient generation of frequency-tunable few-cycle pulses in the infrared, optical, and ultraviolet ranges.

The nonlinear wave mixing and associated parametric frequency conversion present one of the most successful ways for generation of ultrashort electromagnetic pulses in infrared, optical, and ultraviolet bands (including generation of extremely short few-cycle electromagnetic pulses). As a working medium, such generation usually utilizes nonlinear crystals where the low-order wave mixing (three- of four-wave mixing) can take place. In this work, we study the atypical multiwave (high-order) mixing that accompanies ionization of a medium in a strong field of the ultrashort laser pulse and show how this wave mixing may result in generation of few-cycle electromagnetic pulses in infrared, optical, and ultraviolet bands. When the generation of extremely short few-cycle pulses is considered, the method that is proposed here and is based on the ionization-induced multiwave mixing has a number of advantages over the parametric conversion employing nonlinear crystals. Some advantages originate directly from the high-order nature of the strong-field ionization: the large number of mixed waves causes the duration of the generated pulse to be much shorter than the duration of the ionizing laser pulse so that the direct generation of the much shorter pulses is possible (and there may be no need for external compression or other additional efforts for generation of few-cycle pulses) [1]. Moreover, the large number of mixed waves results in a numerous set of generated combination frequencies, which can lie in a broad spectral range and be both lower and higher than the frequencies of the ionizing pulse.

In this work, we study the most basic configuration for ionization-induced wave mixing where a two- or three-color ionizing pulse is just focused in a gas. We calculate analytically and numerically the free-electron currents excited at combination frequencies of the ionizing pulse and the electromagnetic radiation generated by these currents. The analytical and numerical results show that the duration of the generated pulse is equal to the ionization duration and may be close to the sub-cycle limit for the generation in the mid-infrared range and may be as short as of 1–2 fs in the ultraviolet range (when three-color pulses are employed). The carrier-envelope phase in the generated pulse is determined by the phase shifts between one-color components of the ionizing pulse and may be stabilized if the corresponding phase shifts are stabilized. The spectral shape of the generated pulse is usually smooth enough (in contrast to the jagged spectra that often originate from self-phase modulation). The estimations for the radiated energy show that the conversion efficiency can be as high as a few percent (for the mid-infrared band) even in this basic configuration when no efforts are made to improve synchronism conditions and the propagation distance. The obtained analytical formulas describe the main scale dependences of the properties (amplitude, duration, carrier-envelope phase, and spectral shape) of generated pulses on the parameters of the ionizing laser pulse (intensities of the one-color components, duration, and phase structure) and reveal the similarities and dissimilarities between the ionization-induced wavemixing under consideration and the low-order wavemixing in a common nonlinear media. This may prove useful for the identification of the ionization-induced wavemixing in the experiments as well as for designing and optimizing schemes for efficient generation of the few-cycle pulses.

References

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