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Linear and Non-Linear Carrier-Envelope Phase Difference Effects in Interactions of Ultra-Short Laser Pulses with a Metal Nano-Layer

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On the basis of classical electrodynamics the reflection and transmission of an ultra-short laser pulse impinging on a metal nano-layer have been analysed. The thickness of the layer was assumed to be of the order of 2-10 nm, and the metallic electrons were represented by a surface current density at the plane boundary of a dielectric substrate. It has been shown that in the scattered fields a non-oscillatory wake-field appears following the main pulse with an exponential decay and with a definite sign of the electric and magnetic fields. The characteristic time of these wake-fields is inversely proportional to the square of the plasma frequency and to the thickness of the metal nano-layer, and can be of order or larger then the original pulse duration. The magnitude of these wake-fields is proportional with the incoming field strength – so this is a linear effect – and the definite sign of them is governed by the cosine of the carrier-envelope phase difference of the incoming ultrashort laser pulse. As a consequence, when we let such a wake-field excite the electrons of a secondary target – say a plasma, a metal surface or a gas – we obtain 100 percent modulation depth in the electron signal in a given direction. This scheeme can perhaps serve as a basis for the construction of a robust linear carrier-envelope phase difference meter.
At relativistic laser intensities the target becomes a plasma layer generated, e. g. by the rising part of the incoming laser pulse. An approximate analytic solution has been given for the system of the coupled Maxwell-Lorentz equations describing the dynamics of the surface current (representing the plasma electrons) and the composite radiation field. With the help of these solutions the Fourier components of the reflected and transmitted radiation have been calculated. The nonlinearities stemming from the relativistic kinematics lead to the appearance of higher-order harmonics in the scattered spectra. In general, the harmonic peaks are down-shifted due to the presence of the intensity-dependent factors of order of 15-65 per cent in case of an incoming field of intensity 2×10^{19}W/cm^2. This phenomenon is analogous to the famous intensity-dependent frequency shift appearing in the high-intensity Compton scattering on a single electron. In our analysis particular attention has been paid to the role of the carrier-envelope phase difference of the incoming few-cycle laser pulse. For instance the 4th harmonic peak strongly depends on the carrier-envelope phase difference with a modulation being more than 20 percent. It is also shown that the spectrum has a long tail where the heights of the peaks vary practically within one order of magnitude in the frequency range considered. By Fourier synthesising the components from this "plateau" region of the higher-harmonic spectrum, attosecond pulses have been obtained.