Pulse shape calculations

The supercontinuum generation in the sapphire plate is simulated for the particularly tailored pulse shapes. This is performed by applying the nonlinear Schrödinger equation which describes the propagation of the electric field of a laser pulse inside the medium including linear and nonlinear source terms. The nonlinear partial differential equation is solved numerically by using a variant of the Split-Step Fourier method described in[31]. The calculation of the propagation is performed stepwise where each time the integration is carried out in two steps, a dispersion step and a nonlinear step. With the fast Fourier transform algorithm these simulations can be performed reasonably fast. This enables to include dispersion and nonlinear effects which occur for the propagation of intense laser pulses through a transparent medium. Since the magnitude of these effects increases with the propagated distance a reasonably large number of 64 propagation steps is applied. For the simulation, the material group velocity dispersion GVD = 32409 fs^2/m at the center wavelength of λ_0 = 1028 nm and the nonlinear index of refraction $n_2 = 3 \cdot 10^{-20}$ m^2/W of sapphire are used. Self-phase modulation and self-steepening are included in the calculation.

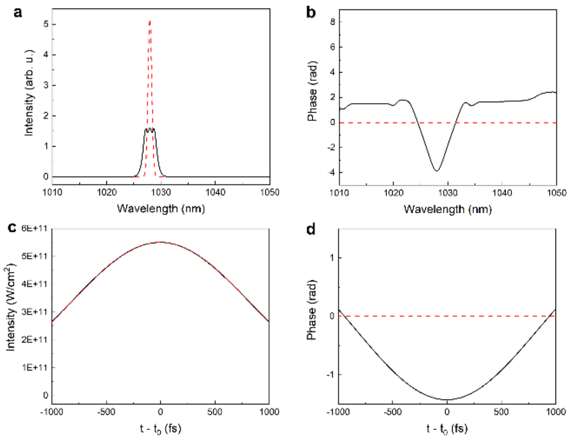

Figure 1: Simulation results for a laser pulse with a full width at half maximum of Δt = 2000 fs after propagation through a 1 mm sapphire plate. The plots present the pulse spectrum (a), the spectral phase (b), the temporal intensity (c), and the temporal phase (d) for the the initial (dashed red) and the propagated pulse (solid black).

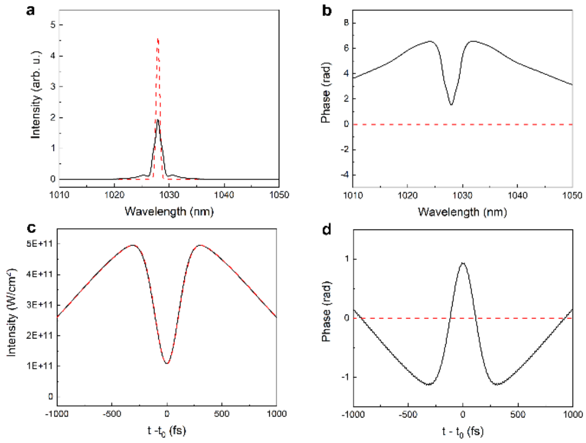

Figure 2: Simulation results for a laser pulse having a full width at half maximum of Δt = 2000 fs with a centered 80% ghost pulse (dip) with Δt = 250 fs after propagation through a 1 mm sapphire crystal. The plots show the spectrum (a), the spectral phase (b), the temporal intensity (c), and phase (d) for the initial (dashed red) and the propagated pulse (solid black). A distinct difference with new features is observed compared to the results without ghost pulse.

Fig. 1 shows the simulation results for a Fourier-limited laser pulse with a full width at half maximum of Δt = 2000 fs after propagation through a 1 mm thick sapphire plate. The intensity is chosen at a magnitude where the spectral broadening starts to be relevant (peak nonlinear phase shift of about π/2 rad), which is in agreement with the experimental values. The plots of Fig. 1 display the spectrum (a), the spectral phase (b), the temporal intensity (c), and the temporal phase (d) after propagation through the crystal (solid black lines). The initial pulse is depicted for comparison (dashed red lines). It can be observed that the spectrum is only barely broadened compared to the initial spectrum having a bandwidth of 0.8 nm and that the temporal intensity is still similar to the incoming pulse shape, which indicates only minor light-matter interactions. The spectral phase shows a weak and almost quadratic shape for the range close to the center wavelength where the spectrum is present. This leads to a small positive chirp of the laser pulse. This chirp is also visible as a broad parabola in the temporal phase which spans the entire pulse duration. Hence, the results are as expected for a weakly nonlinear laser pulse transition through a thin dispersive medium.

Fig. 2 presents the simulation results for a laser pulse with a full width at half maximum of Δt = 2000 fs having a centred 80% ghost pulse (deep dip) with Δt = 250 fs after propagation through a 1 mm sapphire crystal. The intensity is tuned to the same value as in Fig. 1 where the spectral broadening of the long pulse begins. Fig. 2 displays new pulse features of the spectrum (a), the spectral phase (b), the temporal intensity (c), and the temporal phase (d) compared to the results without ghost pulse. Similar as in Fig. 1 (a), the central part of the spectrum is only weakly broadened but new spectral intensities arise at about ±3 nm relative to the center wavelength, which can be attributed to the ghost pulse occurrence (see EDF 4). In the spectral phase plot, the central part around 1028 nm seems unchanged, but at higher and lower wavelengths a broad increased phase range is visible, which is attributed to the ghost pulse. The opposite sign of this phase is evidence for a negative chirp. In the temporal phase, a broad parabolic shape originating from the long pulse is observed, interrupted by a narrower parabola with an opposite signed prefactor during the ghost pulse duration, which indicates a negative chirp close to the central part of the laser pulse.