Electron Pulse Compression with Optical Beat Note
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Abstract: We propose to use optical beat notes to compress electron pulses, which is applicable to electron pulses with a wide range of initial duration.

Measurement of fundamental physics on ultrafast timescales is a cornerstone of modern physics, materials science, and biology. Measuring interactions on femtosecond (fs) timescales requires fs probes [1]. Therefore, compression of electron beams, which are probes par excellence for matter due to their large scattering cross section and high spatial resolution, is of paramount importance. Terahertz (THz) electron compressors have been demonstrated which compress electron pulses from picosecond (ps) to fs timescales [1]. However, the generation efficiency of THz waves is typically low. On the other hand, optical near-field can modulate the free electrons to form a train of micro-bunches of sub-fs duration, where electrons within a fs optical cycle are compressed to a density peak [2]. However, there have not been any previous works indicating the possibility of using optical modulation with fs periodicity to compress the whole ps electron pulse.

In this presentation, we propose an electron compressor using the optical beat note generated by two infrared lasers to achieve effective THz compression without direct THz generation [3]. The schematic of the optical electron pulse compression system is shown in Fig. 1(a). The electron pulse is energy modulated in the vicinity of a nano-structure, which is excited by incident optical fields with two frequencies, and drifts in the free space after the modulation. We take the nano-structure as a dielectric laser accelerator (DLA) which can provide around 1 keV energy modulation within 10 μm interaction distance [2]. Such a large energy modulation is useful in electron compression. When the DLA is illuminated by an unchirped optical pulse with central frequency ω, the transverse deflection forces at the channel center can be cancelled by controlling the driving laser. If an electron with velocity v passes the center of the modulation stage (z = 0) at time τ, the energy modulation on this electron is approximately ΔE(τ) = EΔA(τ)cos(ωτ − φ), where E and φ represent the magnitude and phase of the energy modulation respectively, and ΔA(τ) describes the slow-varying pulse envelope of the pulse with unity peak value, e.g., a Gaussian function ΔA(τ) = 1 − 4t^2/Δp^2, where Δp is the FWHM of the optical pulse.

Under the illumination of two optical pulses with central frequencies ω1 and ω2 (assuming ω1 > ω2), same pulse envelope, and a beat node at τ = 0, the energy modulation becomes

\[ \Delta E(\tau) = 2E\Delta A(\tau) \sin \left( \frac{\omega_1 - \omega_2}{2} \tau \right) \cos \left( \frac{\omega_1 + \omega_2}{2} \tau \right), \]

where we call the last term the fast-oscillating part and the rest the slow-varying part (ΔE(τ)). We sketch the energy modulation near the beat node in Fig. 1(d). We assume that the electron pulse center passes the modulation stage at τ = 0. The time separation between neighbour beat nodes should be smaller than the driving laser duration.
Fig. 2. (a) Zoom-in view of the energy modulation with the first 4 harmonics of two driving optical pulses (blue). The dashed red curve is the slow-varying $\Delta E(\tau)$. (b) Electron density distribution before (yellow) and after the compression with only fundamental frequencies (blue) or first 4 harmonics (red) with modulation amplitude $\delta = 400$ eV. The inset shows a zoom-in view of the peak. (c) FWHM (blue) and peak ratio (red) of the compressed electron pulse as a function of the energy modulation amplitude. Solid line is the theoretical FWHM $\delta E_0/\delta'(\omega_1 - \omega_2)$. Dashed line represents the modulation with the slow-varying modulation $\Delta E(\tau)$ ($N=1$). The circle, diamond, triangle and square represent respectively the compression with the first 1, 2, 3, and 4 harmonic(s).

($\Delta_p$) and much larger than the electron pulse duration ($\Delta_e$), such that the electron pulse is almost entirely within a beat node near $\tau = 0$. To satisfy these requirements, we choose $(\omega_1 - \omega_2)/2\pi = 1/4\Delta_e$ and $\Delta_p = 20\Delta_e$. We set $\Delta_e = 0.1$ ps in Fig. 1 ($\Delta_e = 1$ ps in Fig. 2), and $\omega_0/2\pi = 133.84$ THz.

The compression mechanism is as following. The slow-varying part in Eq. 1 can be linearized near $\tau = 0$, $\Delta E(\tau) \approx \alpha \delta'(\omega_1 - \omega_2)\tau$, $\alpha = 1$. With this energy modulation, the leading part of the electron pulse ($\tau < 0$) loses energy and the trailing part of the electron pulse ($\tau > 0$) gains energy. The electron pulse reaches optimal bunching after a free-space drift length $L_p = mc^2\beta^2\gamma^2/|\alpha \delta'(\omega_1 - \omega_2)|$, where we assume the electron pulse has negligible initial energy spread with respect to $\delta$, $\beta = \nu/c$, and $\gamma = 1/\sqrt{1-\beta^2}$. In this ideal limit, the electron pulse with initial duration $\Delta_e$ and energy spread $\delta E_0$ can be compressed to a pulse with duration $\delta E_0/\alpha \delta'(\omega_1 - \omega_2)$.

In our optical compressor, the initial electron pulse, whose distribution in the energy-time phase space is shown in Fig. 1(b), experiences an energy modulation given by Eq. (1). Immediately after the modulation, its phase-space distribution is shown by Fig. 1(c). We notice that, at time $\tau_m = 4\pi m/(\omega_1 + \omega_2)$, where $m$ is an integer, the curve $\Delta E(\tau)$ is tangent to the slow-varying part $\Delta E'(\tau)$. Thus, these clusters of electrons with $\tau$ near $\tau_m$ as indicated by the orange circles in Fig. 1(d), can be bunched. After the modulation, the electron pulse undergoes a shear transform in the energy-time phase space when it drifts in the free space, as indicated by the orange arrows in Fig. 1(d). Figure 1(e) shows the final phase-space distribution, where the clusters with $\Delta \tau \approx 0$ but different energies form the density peak. As a numerical demonstration, we assume that the electrons have initial kinetic energy 57 keV and energy spread 1 eV, with an initial duration $\Delta_e = 1$ ps (Fig. 2(b), orange curve). With modulation strength $\delta = 400$ eV and an optimal free-space drift of 44.6 mm, the electron density distribution is shown by the blue curve in Fig. 2(b). We find a dominant density peak at the electron pulse center, with a FWHM duration of 2.3 fs.

The limitation of this optical electron compressor is the small peak ratio, i.e., only a small portion of the electrons can be captured in the central density peak after compression. We find that this limitation can be ameliorated if higher harmonics are included in the optical pulses. As a demonstration, we include the first 4 harmonics of $\omega_0$ and $\omega_2$ with proper amplitudes [3]. From the energy modulation (Fig. 2(a)), we observe that (1) the slow-varying $\Delta E(\tau)$ is close to a linear function around $\tau = 0$, and (2) when $\Delta E(\tau)$ is tangent to $\Delta E'(\tau)$ at $\tau_m = 4\pi m/(\omega_1 + \omega_2)$, larger portion of electrons experience energy modulation given by the slow-varying part. These two aspects are the two main reasons for the increased peak ratio. In our numerical example (Fig. 2(b)), the peak ratio is increased from 3% with $N = 1$ to 21% with $N = 4$. We also show the FWHM of the compressed electron pulse and the peak ratio as a function of the modulation amplitude for different numbers of harmonics, in comparison with theory and slow-varying THz modulation (Fig. 2(c)). These results indicate that the optical compression has performance comparable to THz compression, while being more efficient and compact.

References
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