Superradiant pulse compression using free-carrier plasma

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Free-carrier plasma can be used as an effective nonlinear medium for pulse compression. In the backward Raman amplifier geometry, the lower-frequency seed can extract most of the long pump energy through the mechanism of nonlinear superradiance. Filamentation is avoided due to strong dependence of the Raman instability growth rate on the wavenumber.

The motivation for this work is to introduce a novel method of compressing laser pulses to femtosecond duration using tenuous plasma as the nonlinear medium for parametric conversion of the energy of a long higher-frequency laser beam into the energy of a short lower-frequency laser pulse. The standard approach to generating high-intensity ultra-short laser pulses is Chirped Pulse Amplification [1] (CPA), in which a laser pulse is stretched, amplified, and re-compressed. CPA-based optical systems have been shown to generate sub-picosecond petawatt laser pulses [2, 3] with up to 500 J per pulse. The pulse energy is limited by the thermal damage to the compression gratings which become large and expensive for kJ pulses.

An alternative approach to pulse compression, discussed in this paper, utilizes the free-electron plasma as a nonlinear medium for parametric conversion of the energy of a long laser pump into a much shorter (femtoseconds) counter-propagating seed. This originally ultra-short pulse can be amplified by several orders of magnitude over less than a centimeter length of the plasma [4]. There are several advantages in using the free-carrier plasma. First, there is no thermal damage threshold – fresh plasma can be used for each shot. Second, the time responce of the plasma is ω_p^{-1}, which corresponds to 3fs for $n_0 = 10^{19}\mathrm{cm}^{-3}$.

Moreover, the counter-propagating geometry enables us to utilize a remarkable property of the cold plasma as a parametric medium: its χ_3 coefficient has a very strong dependence on the wavenumber difference Δk between the two interacting laser pulses. In particular, for counter and co-propagating lasers ($\uparrow\downarrow$ and $\uparrow\uparrow$, respectively) the ratio of the χ_3 coefficients is $\chi_3(\uparrow\downarrow)/\chi_3(\uparrow\uparrow) \approx 4\omega_0^2/\omega_p^2$ [6], where ω_0 and ω_1 are the frequencies of the amplified signal and the pump, $\omega_p = (4\pi e^2 n_0/m)^{1/2}$ is the plasma frequency, n_0, $-e$, and m are the plasma density, electron charge, and mass, respectively. In a tenuos plasma this ratio can be several hundred. This distinguishes parametric amplification in cold electron plasma from that in gasses, liquids, and fibers. Therefore, a short pulse can be rapidly amplified by *backscattering* a counter-propagating pump without suffering from forward-propagating instabilities (such as Raman forward scattering and filamentation). χ_3 of

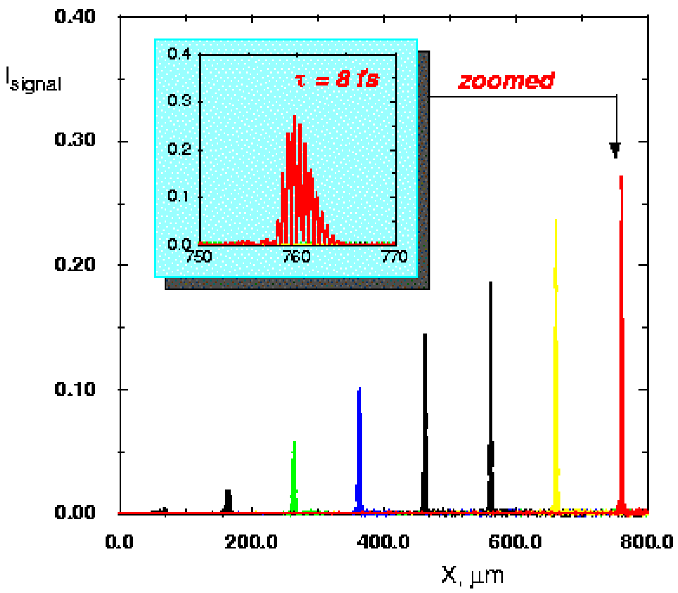
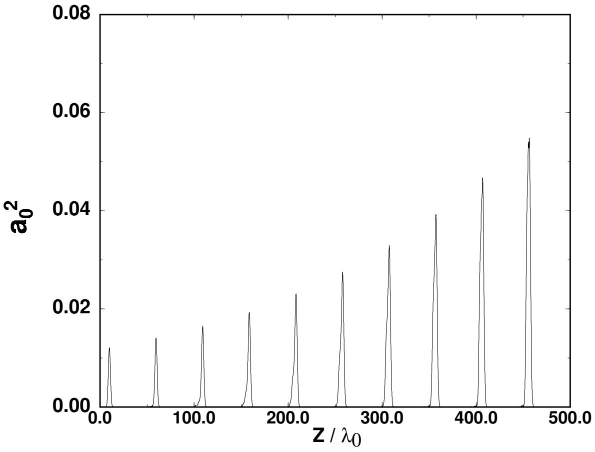


Fig. 1. Amplification of 10 fs pulse with initial intensity $I_0 = 3.5 \times 10^{15}$ W/cm^2 by a counter-propagating pump with the same intensity $I_1 = I_0$ inside the plasma with density $n_0 = 1.5 \times 10^{19}$ cm^{-3}. After 700 microns the signal intensity grows by factor 60.

the electron plasma can be understood as follows: electron density perturbation is ponderomotively driven by the periodic intensity pattern produced by the interference between the pumping beam (PB) and the amplified beam (AB). This density perturbation then serves as a grating which scatters the pump.

We have identified a novel regime of pulse compression in plasma which is insensitive to the fluctuations of the plasma density and to the precize detuning between the pump and the signal. In this superradiant amplification regime a finite-amplitude seed pulse of duration $\tau_L \sim 2\omega_p^{-1}$ is injected. Accessing this regime requires a sufficiently intense initial pulse: $4\omega_0^2 a_0 a_1 \geq \omega_p^2$, where $a_{0,1} = eA_{0,1}/mc^2$ are the normalized vector



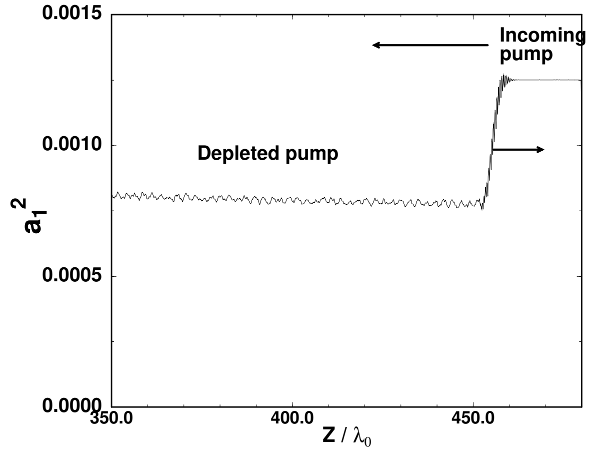


Fig. 2. Large pump depletion regime modeled by PIC simulation. Pump $a_1 = 0.025$, initial signal $a_0 = 0.07$ and $\tau_L = 1/\omega_p$, plasma $n_0 = 10^{19}$ cm^{-3}. Left figure: short pulse amplification (series of snapshots); right figure: 40% pump depletion by the short pulse.

potentials of the AB and PB, respectively. When this condition is satisfied, electron motion is determined by the ponderomotive force and not by the space-charge electric field of the plasma wave. so that the resonance condition for the plasma wave excitation $\Delta\omega = -\omega_p$ needn't be exactly satisfied.

Numerical simulation of the pulse amplification in this regime using particle-in-cell (PIC) numerical code is shown in Fig. 1, where the amplification of a short (initially $\tau_L = 10fs$) $\lambda_0 = 1\mu$m laser pulse is demonstrated as it propagates through 700μm of the plasma while interacting with a long counter-propagating pulse whose frequency is 3% higher. Simulation parameters are given in the caption. As Fig. 1 indicates, the short pulse intensity is amplified by a factor 60 while its duration shrinks to about 8 fs (see the inset). We demonstrated numerically that the efficiency of energy conversion from the long to short pulse can be quite high. In Fig. 2 a collision between a somewhat stronger short pulse with $a_0 = 0.07$ ($I_0 = 1.3 \times 10^{16}$ W/cm^2) and the pump with $a_1 = 0.025$ ($I_0 = 1.7 \times 10^{15}$ W/cm^2) is demonstrated. As Fig. 2(b) indicates, the pump is 40% depleted by the short pulse.

Superradiant amplification is a strongly nonlinear process. The dependence of the short pulse intensity and duration on the propagation distance z can be qualitatively estimated as

$$|a_0|^2 \sim \frac{|a_1|^2 \omega_p^4 z^2}{16\omega_0^2 c^2} \qquad \tau_L \approx \frac{2}{\omega_p a_1} \left(\frac{c}{\omega_0 z} \right)^{1/2} \tag{1}$$

Quadratic dependence of the short pulse intensity on the propagation distance (and, therefore, on the number of electrons $\mathcal{N}$ encountered by the pulse) gives this amplification process its name [7]. The dependence of τ_L has a somewhat unusual scaling $1/\sqrt{\mathcal{N}}$. This is because the pulse narrowing is caused by the laser recoil and not by the pump depletion. In particular, the characteristic bounce frequency of a plasma electron inside the ponderomotive potential created by the interference of the pump and the pulse is given by $\omega_B = 2\omega_0\sqrt{a_0 a_1}$. In the Compton regime frequency replaces the Rabi frequency which, in atomic systems, scales $\sim a_0$.

The intriguing possibility is to use the free carriers (electrons and holes) in a solid medium, such as a semi-metal or a heavily-doped semiconductor, instead of the gaseous plasma. Since the laser intensity would be limited by the material damage, Raman amplification [5] ($\Delta\omega = -\omega_p$) would have to be used.

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