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Enhancement in self-compression due to co-propagating laser pulse in plasma

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ABSTRACT

The study proposes enhancement in self-compression of the laser pulse with relativistic nonlinearity in a plasma. It is presented that, a low-intensity laser pulse can tune the pulse duration and peak intensity of the high-intensity laser pulse. The coupled modified nonlinear Schrodinger equations (MNLS) have been established for both laser pulses in plasma. The enhancement in compression of the high-intensity laser pulse is solved by numerical methods. The nonlinearity of plasma, self-phase modulation (SPM), and group velocity dispersion (GVD) compress the laser pulse to the extremely short duration high peak intensity laser pulse. As a result, it is observed that the compression of the high-intensity laser pulse is highly sensitive to the combined intensity of both laser pulses, plasma density and even a small walkoff between two pulses can affect the high-intensity laser pulse compression.

1. Introduction

Nowadays, the high power few-cycle pulses have an important aspect of extreme nonlinear optics and laser physics. These pulses are specially used to measure the electron dynamics in high-resolution time-domain spectroscopy [1] and generation of attosecond pulses [2]. Therefore, experiments are sensitive to high power few-cycle laser pulses rather than high-intensity laser pulses. However, the generation of few-cycle laser pulses with high power is still challenging. The generation of high power few-cycle pulses is based on solid-state laser systems, particularly on Ti: sapphire laser pulses with 25–30 fs pulse duration up to petawatt (PW) energy level [3] and second few-cycle pulses of duration down to 10 fs of Ti: sapphire laser at 800 nm wavelength, depending on the (optical parametric chirp pulse amplification technique) [4]. However, the main limitations of these techniques come from the efficiency of compression is less than 10 percent and the power of the laser is also not exceeded the self-focusing. An alternative way to produce high energy, few-cycle pulse using ionization-induced [5] self-compression effect.

The ultra-intense laser pulse interactions with matter provide various interesting physical phenomena. Which have been observed, such as attosecond X-ray pulses [6], generation of high harmonics [7], relativistic electron mirrors [8] and laser-particle accelerator. These days, intense ultra-short laser pulses are used for measurements of pump–probe with high time resolution [9], double-slit interferometry on the attosecond time scale [10]. The chirped pulse amplification (CPA) method [11], has allowed the generation of short pulses with pulse duration as short as 100 fs and peak powers varying from 100 TW (Terawatt) to 1 Petawatt. However, the most challenging and limitation of this scheme is, if the laser power is more than 50 TW, the laser having pulse duration 30 fs is limited by propagating through amplifiers because of finite spectral bandwidth. Moreover, the ultra-short laser pulses would be of attentiveness as they could advantageous to high peak power without hiking the cost and size of the laser system and conserving laser pulse energy. In addition, there is a substitute to the CPA method, through stimulated Raman backscattering [12], in which pulse duration of the amplified seed pulse may compress to the pulse duration of the order of plasma wavelength. The laser pulse of duration 5 fs have been generated using self-phase modulation in gas [13]. However, this scheme is not useful for laser system having 100 TW peak power, as it is limited by ionization in the gas.

For this context, use of plasmas medium is one of the best ways to compress the laser pulse. It can sustain extremely high peak intensity laser pulse exposure than diffraction gratings, optical crystals, and nonlinear optical material. Moreover, the interaction of short pulse with plasma gives the relativistic nonlinearities, which will appropriate for laser pulse compression. Indeed, the appearance of various studies, including theoretical and numerical have been seen in the past year on laser pulse self-compression.

Shvets et al. [14], have investigated the super-radiant amplification of ultrashort laser pulses in plasma, in which a short pulse can be

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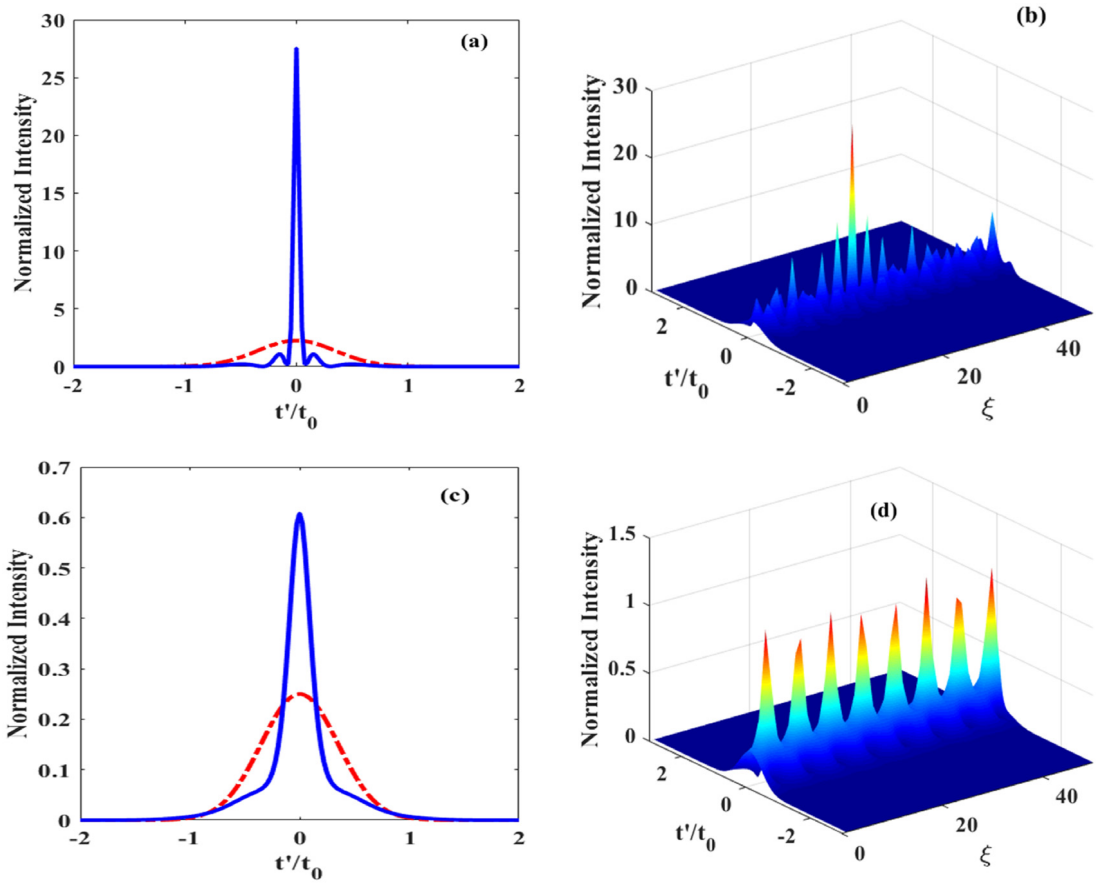

Fig. 1. (Walk-off parameter $L_W = 0$), (a) 2D plot of the normalized initial intensity and compressed pulse intensity of high-intensity laser pulse at distances ($z = 0$ and 65 μm). In Fig. 1(b) 3D propagation of high-intensity laser pulse with normalized distance (ξ). The 2D and 3D plot for low-intensity laser pulse is presented in Fig. 1(c–d) for wavelength of high-intensity laser pulse $\lambda_1 = 1064$ nm, wavelength of low-intensity laser pulse $\lambda_1 = 800$ nm, normalized initial pulse durations of high intensity and low-intensity laser pulses are t_{01} and $t_{02} = 50$ fs, the normalized initial intensity of high-intensity laser and low-intensity laser pulse are $a_1^2 = 2$ and $a_2^2 = 0.2$ and plasma density $n_e = 0.1 \times 10^{19}$ cm^{-3} is same for all.

super-radiantly amplified by the counter-propagating low-intensity laser pulse. A model have been proposed, for super-radiant amplification of a single laser pulse of a duration of the order of femtosecond by a counter-propagating long pulse in underdense plasma [15]. The efficient compression in femtosecond duration laser pulse can be seen, when a short pulse with smaller-frequency collides with a long pulse with a high frequency in a tenuous plasma [16]. The compression of laser pulses due to co-propagating laser pulses optical fiber have been reported by many [17–19]. The temporal shortening of the laser pulse in nonlinear plasma have been studied by using particle in cell simulations PIC in 3D [20]. However, the self-compression of the laser pulse in ionized plasma was investigated [21], by using geometrical focusing and three-dimensional spatiotemporal reshaping. An intense laser pulse having relativistic intensity lead to self-compression due to wake-field generation [22,23]. It is challenging for the researcher to get homogeneous temporal pulse compression of the focusable spatial profile. Many theoretical works have done for self-compression of laser pulse using a single laser pulse in magnetized and the un-magnetized plasma [24–30]; the key physics involving group velocity dispersion, self-phase modulation and plasma wave, which leads to generating short pulses inside the plasma, these observations have been studied by changing magnetic field, plasma density, and amplitude of laser pulse. But presently, we have added a new way to generate high-intensity, short pulses via co-propagating low-intensity laser pulse with a high-intensity laser pulse.

The consequence of self-phase modulation (SPM) on the spectrum of pulse have been observed in silica fibers [31,32], as well as in bulk glasses [33]. In most pump–probe experiments [31,34], SPM induced spectral change without a significant change in shape of the pulse. When both probe and pump pulse is launched together with an intense pump pulse. The probe pulse develops an oscillatory structure and its spectrum generally broadened. This arises due to SPM applies a frequency chirp on the probe pulse. Moreover, the probe spectrum becomes asymmetric or symmetric depending on the delay between the probe and pump pulses. The asymmetric probe spectrum can be perceived by applying nonlinear phase-shifts schemes that incorporate the effects of the pulse walk-off [31]. In practice, the probe and pump pulses walk off from each other because of their difference in group velocities. Therefore, the effects of pulse walk-off lead to an SPM-induced frequency shift [34] of probe pulse spectrum. During the SPM interaction, when group velocity dispersion (GVD) coefficient dominant, both the spectrum and the shape of the probe pulses are expected to be influenced significantly by the presence of pump pulses.

Previously we studied [35], the self-compression of two copropagating laser pulses inside plasma having relativistic nonlinearity. We considered the semi-analytical approach to solving the nonlinear Schrodinger equation for both laser pulses. To account the effect of envelope part, we have to simulate the electromagnetic wave equation without any further analytical simplification. Moreover, previously we assumed the frequencies of two laser pulses are same that the mismatch factor in group velocities of two laser pulses is small enough to prevent the walk-off between the two laser pulses over the propagation range. In practice, two laser pulse frequencies should not be sufficiently close, otherwise, it is difficult to separate the compressed high-intensity laser pulse from the low-intensity laser pulse at the boundary of the plasma channel. When an intense laser pulse propagates inside plasma it gets

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