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라만 후방향산란을 이용한 레이저 펄스 증폭 가시화

이해준† · 김진철* · 김창범** · 김광훈** · 김종욱** · 석희용**

Visualization of Laser Pulse Amplification by Raman Backscattering

Hae-June Lee† · Jin-Cheol Kim* · Changbum Kim** · Guang-Hoon Kim** · Jong-Uk Kim** · Hy-yong Suk **

Abstract

A one-dimensional fluid model has been established for Raman amplification of a short laser pulse in a plasma by a counter-propagating pump. The laser pulse is amplified with a large gain and also may be compressed by nonlinear three-wave interactions. The spatiotemporal evolutions of the seed and the pump pulses were visualized for linear and nonlinear regimes, and the transition from regular to chaotic behavior of subsidiary pulses was investigated with variation of pump intensity.

Key Words : Laser Amplification (레이저 증폭), Raman Backscattering (라만 후방향산란), Computational Visualization(전산 가시화)

1. INTRODUCTION

It is necessary to generate an ultrahigh intensity sub-picosecond laser pulse for the applications to the inertial confinement fusion or advanced accelerators using laser-induced plasmas. For the achievement of high laser power, the chirped pulse amplification (CPA) method[1] is widely used. However, the method is incapable of amplifying a laser pulse having energy greater than kJ because the gratings needed to compress and stretch the laser pulse should be very large and are very expensive.

By colliding a short seed pulse with a long pump pulse in a plasma, it is possible to intensively amplify the seed pulse by drawing energy from the pump[2]. Ordinarily, the laser pulses would simply pass through one another, but the presence of the plasma allows an interaction between the two laser pulses via a Langmuir wave. Energy transfer happens from the pump to a seed pulse by the three-wave interaction. The amplification was verified experimentally[3] and numerically with relativistic and electromagnetic particle-in-cell (PIC) simulations for one-dimensional[4] and two-dimensional[5] models.

A fluid model needs less computation time and is simpler than PIC simulation to study the effect of each parameter, and thus we established one for the envelopes of the laser pulses and the plasma wave, which follow conventional formalism of three-wave interactions.

In this study, we investigate the characteristics of the laser pulse amplification with a fluid model and report the evolution of the seed and the pump laser pulses for various pump intensity.

2. MODEL DESCRIPTION

The governing equations of the envelopes for the seed and the pump pulses and the plasma wave are

$$\frac{\partial f}{\partial t} + i\delta\omega f = -\frac{c}{4}k_f a_1^* a_0,$$

$$\frac{\partial a_1}{\partial t} + v_{g,1}\frac{\partial a_1}{\partial x} = -\frac{c}{4}k_f \frac{\omega_p}{\omega_1} a_0 f^*,$$

$$\frac{\partial a_0}{\partial t} + v_{g,0}\frac{\partial a_0}{\partial x} = \frac{c}{4}k_f \frac{\omega_p}{\omega_0} a_1 f,$$

where $f = eE_x / mc\omega_p$ is the normalized field of the plasma wave with electron plasma frequency ω_p, a_s and ω_s are normalized vector potential and frequency with indices s=0 and 1, which represent pump and seed pulses propagating to the left and to the right respectively. $k_f \equiv k_1 + k_0$ is the sum of the

† Korea Electrotechnology Research Institute
Center for Advanced Accelerators
E-mail: leehj@keri.re.kr
* Pohang University of Science and Technology
** Korea Electrotechnology Research Institute

laser wavenumbers, $v_{g,s} = c^2 k_s / \omega_s$ is the group velocity of each pulse, and $\delta\omega = \omega_0 - \omega_1 - \omega_p$ is frequency detuning factor. The amplification is maximized when the three waves satisfy the matching condition of Raman backscattering, $\omega_0 = \omega_1 + \omega_p$.

3. RESULTS

Figure 1 shows a typical result of the seed pulse amplification. The seed energy has been amplified more than 150 times during 5 ps and the pulse width has been compressed almost by half. At initial time, when $\omega_B \equiv 2\omega_1\sqrt{a_0 a_1} < \omega_p$ (linear regime), the peak intensity increases exponentially as shown in Fig. 1(f) and the pulse width increases as shown in Fig. 1(e) for $t < 1.3$ ps. After the seed pulse has been amplified enough, 100% of pump depletion happens [Fig. 1(b)] and ω_B becomes larger than ω_p (nonlinear regime), which means nonlinear ponderomotive force is larger than the space charge force of the plasma. The energy growth is proportional to t and the pulse width is compressed in nonlinear regime[6]. The compression occurs because the rear part of the seed cannot be supplied with energy from the pump. Moreover, the rear part of seed pulse gives its energy to the pump again by three wave interaction so that the restored pump amplifies the seed behind the main peak again, and thus subsidiary pulses are generated as shown in Fig. 1(c). However, more than 80% of the total seed energy is concentrated in the first pulse which we want to utilize.

Figures 2-5 show contour plots of spatiotemporal evolutions of the seed and the pump pulses for different pump amplitude, a_0= 0.01, 0.03, 0.05, and 0.07. The other parameters are the same as those mentioned in Fig. 1. The system length is fixed to be 2 mm. The pump pulse is incident from the boundary at x =2 mm and the seed pulse is launched at the boundary x =0 with a time delay of 5.5 ps. The two pulses encounter each other at $t \approx 6.3$ ps. In Figs. 2-5, the seed amplitude was plotted in log scale while the pump amplitude in linear scale.

When a_0= 0.01, it is in a linear regime at initial time and thus the pulse width of the main peak is broadened until $t < 8$ ps, and after then start to be compressed as shown in Fig. 2. The subsidiary pulses show regular and moderate behavior. When a_0= 0.03, pulse compression happens much earlier as shown in Fig. 3. Even for this case, the subsidiary pulses still show regular and moderate behavior. When a_0= 0.05, an irregular pattern happens as shown in Fig. 4. There is an subsidiary peak, that propagates with oscillation with slower speed than the main peak. The spatial correlation is weak among the subsidiary peaks. When the pump energy is increased to a_0= 0.07, more chaotic behavior happens and spatial correlation is very weak. There are more oscillating subsidiary peaks propagating very slowly compared with the main peak as shown in Fig. 5(a). All these behaviors are related to spatiotemporal chaos in stimulated Raman backscattering[7].

4. CONCLUSIONS

Amplification of a short laser pulse through stimulated Raman backscattering was simulated with one-dimensional envelope equations of the laser pulses and the plasma wave. A laser pulse is amplified intensively by a counter-propagating pump in a plasma when the matching condition is satisfied. Moreover, the laser pulse is compressed from nonlinear interaction for large laser intensity. Transition from regular to chaotic motion of the subsidiary pulses was observed with increasing pump intensity.

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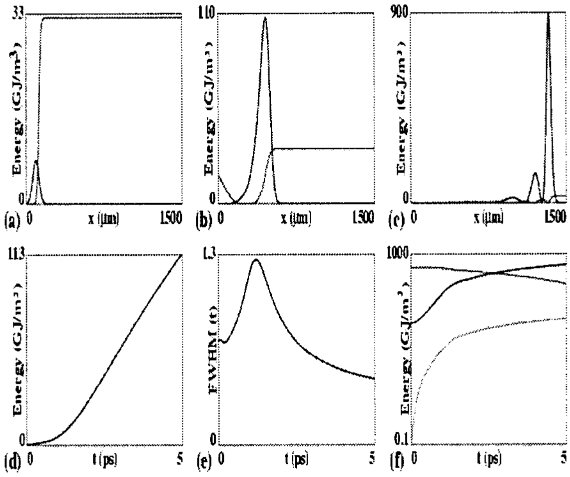

Figure 1. Simulation results of laser pulse amplification with initial quantities of $a_0 = 0.01$, $a_1 = 0.005$, and $\omega_p / \omega_1 = 0.02$. Shown are the energy densities of the seed (blue) and the pump (red) at (a) t=0, (b) t=1.35 ps, and (c) t= 4.1 ps. Also shown are the time evolutions of (a) peak energy density of the seed, (e) full width at half maximum (FWHM) of the seed, and (f) energies of

the seed (blue), the pump (red), and the plasma wave (green) in log scale.

(a)

(b)

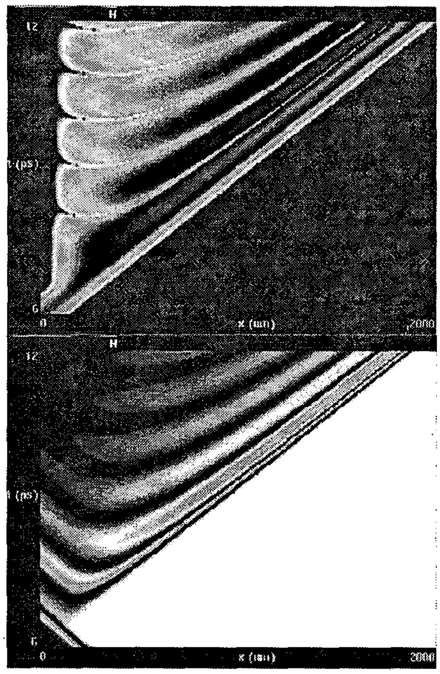

Figure 2. Spatiotemporal evolutions of (a) the seed and (b) the pump pulses for $a_0 = 0.01$.

(a)

(b)

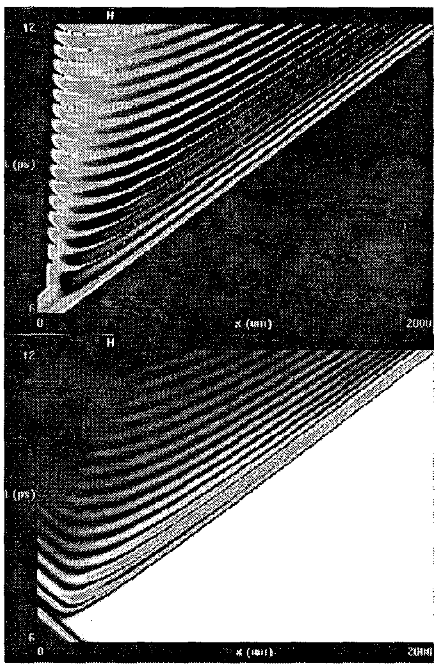

Figure 3. Spatiotemporal evolutions of (a) the seed and (b) the pump pulses for $a_0 = 0.03$.

(a)

(b)

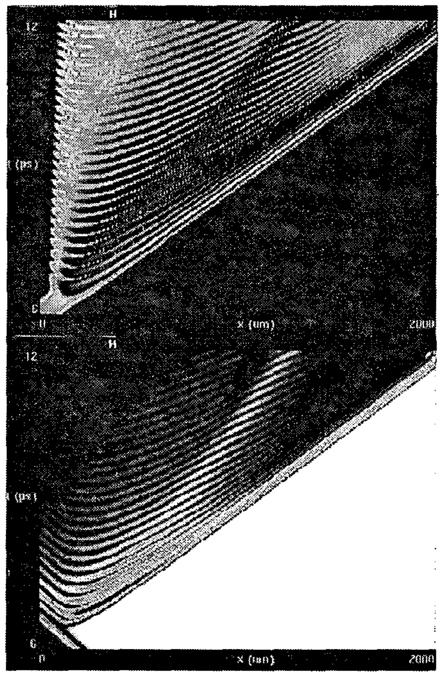

Figure 4. Spatiotemporal evolutions of (a) the seed and (b) the pump pulses for $a_0 = 0.05$.

(a)

(b)

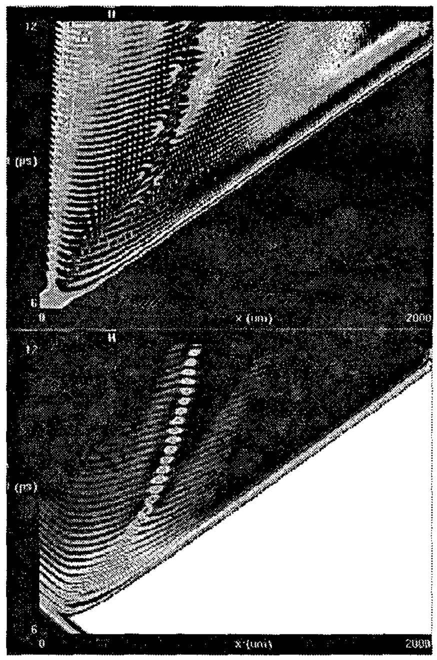

Figure 5. Spatiotemporal evolutions of (a) the seed and (b) the pump pulses for $a_0 = 0.07$.

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