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Controlling ultrashort intense laser pulses by plasma Bragg gratings with ultrahigh damage threshold

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Abstract

Propagation of ultrashort intense laser pulses in a plasma Bragg grating induced by two counterpropagating laser pulses has been investigated. Such a plasma grating exhibits an ultrawide photonic band gap, near which strong dispersion appears. It is found that the grating dispersion dominates the dispersion of background plasma by several orders of magnitude. Particle-in-cell (PIC) simulations show light speed reduction, pulse stretching, and chirped pulse compression in the plasma grating. The nonlinear coupled-mode theory agrees well with the PIC results. Because the plasma grating has a much higher damage threshold than the ordinary optical elements made of metal or dielectric, it can be a novel tool for controlling femtosecond intense laser pulses.

Keywords: Photonic band gap; Plasma Bragg grating; Pulse compression; Pulse stretching

Laboratory laser intensities have grown remarkably during recent years due to the method of chirped pulse amplification (CPA) (Strickland & Mourou, 1985). Ultrashort intense lasers lead to a new field of physics, known as high-field science (Batani & Wootton, 2004; Honrubia & Tikhonchuk, 2004), which studies the interaction between ultra-intense radiation and matter (Magunov *et al*., 2003; Chirila *et al*., 2004; Fukuda *et al*., 2004; Limpouch *et al*., 2004).

In CPA, optical gratings are used to chirp and stretch a short pulse. A broadband optical amplifier is then employed to amplify the chirped low-power stretched signal. Finally, complementary gratings then recompress the original, but now highly amplified, signal. Nowadays, a strong motivation for development of the next generation of high-energy petawatt (HEPW) lasers exists. Production of HEPW pulses remains a technical challenge, the primary concern being the high fluence and short-pulse width experienced by the final HEPW optics, i.e., the final compressor grating and beam transport and focusing optics. For the subpicosecond intense laser pulses, the damage threshold (DT) of dielectric (e.g., fused silica) is about 2 J/cm^2 (Perry *et al*., 1999*a*, 1999*b*; Gamaly *et al*., 2002; Jovanovic *et al*., 2004), and the DT of metal (e.g., gold) is about 0.5 J/cm^2 (Gamaly *et al*., 2002).

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Recently, plasma medium was used to focus an ultrashort intense laser pulse and meanwhile improve its temporal contrast by so-called "plasma mirror" (Kapteyn *et al*., 1991; Backus *et al*., 1993; Gold, 1994; Perry *et al*., 1999*a*, 1999*b*; Doumy *et al*., 2004). It is also proposed to generate ultrahigh intense light fields by superradiant Compton scattering (Shvets *et al*., 1998; Dreher, 2004), Raman-scattering amplification (Malkin *et al*., 1999; Ping *et al*., 2004), quasi-soliton amplification between two foils (Shen & Yu, 2002), pulse focusing by relativistic plasma waves (Bulanov *et al*., 2003), and self-compression of laser pulses (Shorokhov *et al*., 2003). The main advantage of the plasma medium for these novel applications is that it has no thermal DT and can sustain extremely high intensities. Most recently, plasma Bragg grating (PBG) induced by two intersecting laser pulses at intensities of about 10^{15} W/cm^2 is well established theoretically by Sheng *et al*. (2003). The ponderomotive force of the interference fields of the two pump pulses pushes the electrons, which further drag the heavy ions through Coulomb force. Finally, an electrically neutral PBG forms, which can last as long as a few picoseconds.

Another similar structure, fiber Bragg gratings (FBGs), was widely investigated (Agrawal, 2001). FBGs have wide applications in wave filtering (Longhi *et al*., 1997), optical switching (Broderick *et al*., 1998; Taverner *et al*., 1998), and pulse compression (Winful, 1985; Eggleton *et al*., 1996, 1997). These periodic structures have a photonic band gap, around which there is strong dispersion. The grating dispersion dominates the dispersion of background medium by several orders of magnitude. The PBG demonstrates similar properties as the FBG as shown in the following. Moreover, the photonic band gap of the PBG is three orders wider than that of a typical FBG (Eggleton *et al.*, 1996, 1997; Agrawal, 2001). Though the PBG have no thermal DT, it can be damaged by the laser ponderomotive force. We find that, for laser pulse with duration of around 100 fs, the ponderomotive DT of the PBG is about a few 10^3 J/cm^2, which is three orders higher than that of the ordinary optical elements made of metal or dielectric. Due to its ultrawide band gap and high DT, the PBG can be a novel device for controlling the femtosecond intense laser pulses. In this paper, we study a few interesting phenomena in the PBG, such as light speed reduction, pulse stretching, chirped-pulse compression.

Figure 1 illustrates the electron density evolution of a part of PBG obtained in our one-dimensional (1D) particle-in-cell (PIC) simulations (Sheng *et al.*, 2003). The rest is the same as the shown part and the ion density evolution is completely identical to the electron density. The PBG with the length $100\lambda_0$ in $0 \leq z \leq 100\lambda_0$ are induced by two counter propagating flat-topped pulses with amplitudes $a = 0.03$ and durations $200\lambda_0$, where λ_0 is wavelength of the pump pulses in vacuum, and a is the normalized vector potential relating to the laser intensity by $I\lambda_0^2/a^2 = 1.37 \times 10^{18}$ Wcm^{-2} μm^2. The pump pulses simultaneously reach the right-and-left boundaries of the initial uniform plasma slab at $t = 0$. Its initial electron density is $n_0 = 0.3n_c$, where $n_c = \pi m_e/e^2\tau_0^2$ is the critical density for the pump pulses is, and $\tau_0 = \lambda_0/c$ is a light cycle. Obviously, the induced PBG is centrosymmetrical against $z = 50\lambda_0$. The PBG begins to build up at $t = 300\tau_0$ and stays at the deepest modulation almost unchanged during $700\tau_0 < t < 1300\tau_0$. The PBG begins to attenuate after $t = 1600\tau_0$, and completely disappears at $t = 2000\tau_0$. The maximum electron density of the PBG can be up to $n_{max} = n_c$, as shown in Figure 1. If not particularly mentioned, we take the initial electron and ion temperatures to be $T_e = 10$ eV and $T_i = 1$ eV, respectively, the mass ratio of ions to electrons $ZM_i/m_e = 5508$ with $Z = 1$ being the ion charge number in the simulations.

It is apparent that the period of the PBG is $\Lambda = \lambda_0/2N_0$, where the refractive index of the background plasma is $N_0 = \sqrt{1 - n_0/n_c}$, the refractive index of the background plasma. According to the well-known Bragg principle, incident light with the Bragg frequency $\omega_B = 2\pi c/\lambda_0$, i.e., the pump light frequency for the PBG is fully reflected by the PBG. The key property of a grating is that Bragg reflection occurs over a range of frequencies centered about the Bragg frequency ω_B (Eggleton *et al.*, 1996, 1997; Agrawal, 2001). At frequencies far away from ω_B, the reflectivity becomes small. The grating transmission spectrum shown in Figure 2 is obtained by injecting the signal light of different frequencies through the PBG shown in Figure 1. The transitivity suggests that the PBG have an ultrawide band gap about 0.12 ω_B, i.e., 96 nm for $\lambda_0 = 800$ nm. The PBG can be a wave filter since the light detuned with frequencies inside the band gap cannot propagate through the grating. The light with frequencies near the band gap edges can propagate, but suffers strong dispersion from the PBG.

To describe the propagation of a signal pulse in the PBG, we start from the 1D wave equation in underdense plasma (Esarey *et al.*, 1997)

$$\left(\frac{\partial^2}{\partial z^2} - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)\vec{a} = \frac{\omega_p^2}{c^2}\frac{\vec{a}}{\gamma}, \tag{1}$$

where $\vec{a} = e\vec{A}/m_e c^2$ is the normalized vector potential, γ the relativistic factor of the electrons, $\omega_p = \sqrt{\pi e^2 n/m_e}$ the plasma frequency, and n the electron density. One can write $\vec{a} = \frac{1}{2}\hat{e}_x[a_+(z,t)\exp(ik_B z - i\omega_B t) + a_-(z,t)\exp(-ik_B z - i\omega_B t) + c.c.]$ for the light field, where k_B is Bragg wave number, $a_\pm$ are the envelopes of the forward and backward propagating modes. For a weakly relativistic laser pulse, $\gamma = \sqrt{1 + \langle|\vec{a}|^2\rangle} \approx 1 + \frac{1}{2}\langle|\vec{a}|^2\rangle$, where $\langle\ \rangle$ represents the

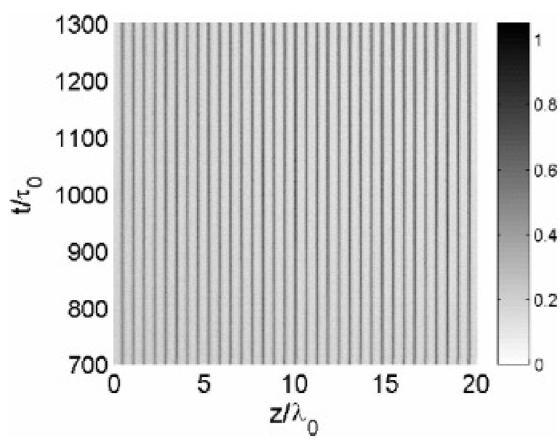

Fig. 1. Spatio-temporal plot (part) of electron density n/n_c of the PBG induced by two counter propagating laser pulses with amplitudes $a = 0.03$ and durations $200\lambda_0$ in uniform plasma with density $0.3n_c$.

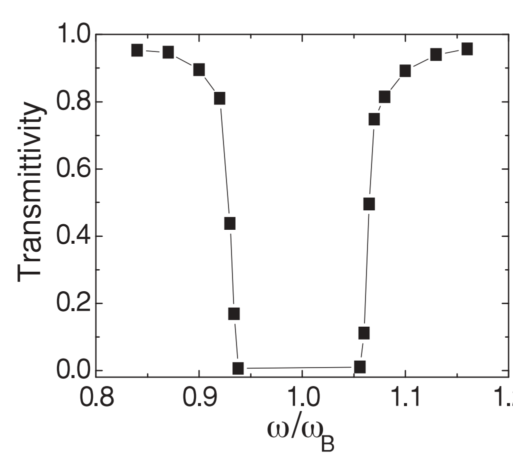

Fig. 2. Transitivity as a function of the signal light frequency through the PBG shown in Figure 1.

time-average over a light cycle. The electron density of the PBG can be written as Fourier series: $n = n_0 + \sum_{m=-\infty}^{\infty} \delta n_m \exp(2imk_B z)$, where δn_m is Fourier component with the spatial period Λ/m. The average of δn_1 between $700\tau_0 < t < 1300\tau_0$ for the PBG in Figure 1 is $\delta n_1 \approx 0.13 n_c$, indicating that our PBG is a deep modulated grating ($\delta n_1 \ll n_0$ corresponding to a shallow grating).

Substituting the above terms into Eq. (1) under the slowly-varying-envelope approximation, we obtain the following nonlinear coupled-mode equations (NLCME)

$$i\left(\frac{1}{v_{g0}}\frac{\partial}{\partial t} + \frac{\partial}{\partial z}\right)a_+ - \chi_{+1}a_- + \Gamma_0(|a_+|^2 + 2|a_-|^2)a_+ + \Gamma_{+1}(|a_-|^2 + 2|a_+|^2)a_- + \Gamma_{-1}a_+^2 a_-^* + \Gamma_{+2}a_-^2 a_+^* = 0, \quad (2)$$

$$i\left(\frac{1}{v_{g0}}\frac{\partial}{\partial t} - \frac{\partial}{\partial z}\right)a_- - \chi_{-1}a_+ + \Gamma_0(|a_-|^2 + 2|a_+|^2)a_- + \Gamma_{-1}(|a_+|^2 + 2|a_-|^2)a_+ + \Gamma_{+1}a_-^2 a_+^* + \Gamma_{-2}a_+^2 a_-^* = 0, \quad (3)$$

where $\chi_{\pm 1} = (\omega_B/2v_{g0})(\delta n_{\pm 1}/n_c)$ is coupling coefficients, $v_{g0} = N_0 c$ is group velocity, and $\Gamma_m = (\omega_B/8v_{g0})(\delta n_m/n_c)$. Since $\delta n_m = \delta n_{-m}$, one can simply define $\chi \equiv \chi_{\pm 1}$, $\Gamma_{|m|} \equiv \Gamma_m$. The second terms on the left-hand sides of Eqs. (2) and (3) are the coupling terms, which lead to the grating dispersion. The third and latter terms refer to the nonlinearity owing to the relativistic electron motion. Generally, since $\Gamma_0 > \Gamma_1 > \Gamma_2$, the effect of these nonlinear terms reduces in turn. When the transitivity is high, i.e., $a_- \ll a_+$, neglecting $|a_-|^2 a_+$ and $\Gamma_{1,2}$ terms in Eqs. (2) and (3), the remainder $\Gamma_0|a_+|^2 a_+$ corresponds to self-phased modulation (SPM) for the forward propagating mode. Eqs. (2) and (3) can also apply to the deep grating structure (Iizuka & Sterke, 2000; Haus *et al.*, 2002). When neglecting $\Gamma_{1,2}$ terms, the left equations can well describe the nonlinear pulse propagation for the shallow grating case (Eggleton *et al.*, 1996, 1997; Agrawal, 2001).

The dispersion relation in the PBG can be obtained by inserting the plane-wave solutions $a_\pm = C_\pm \exp[i(qz - \Delta\omega t)]$ into the linearized Eqs. (2) and (3), where $q = k - k_B$, $\Delta\omega = \omega - \omega_B$ represent the detuning between the wave number (frequency) of the incident light, and the Bragg wave number (frequency) of the grating. This substitution leads to the linear dispersion relation

$$q = \pm\sqrt{\delta^2 - \chi^2}, \quad (4)$$

where $\delta = \Delta\omega/v_{g0}$. This dispersion relation indicates that the PBG has a photonic band gap, i.e., $-\chi < \delta < \chi$, inside which the light cannot propagate because of imaginary q. The band gap width is found explicitly to be $\omega_B \delta n_1/n_c$. For the PBG given in Figure 1 ($\delta n_1 \approx 0.13 n_c$), the band gap width is about $0.13\omega_B$. This agrees well with the transmission spectrum given in Figure 2.

The group velocity of the signal pulse in the grating is found by calculating $V_g = d\omega/dk$ from Eq. (4), leading to

$$V_g = \pm v_{g0}\sqrt{1 - \chi^2/\delta^2}. \quad (5)$$

Eq. (5) indicates that the speed of light decreases to zero at the band gap edges. Eq. (5) (solid line) agrees well with 1D PIC simulation results as displayed in Figure 3. For example, the signal light with $\omega = 0.93\omega_B$ propagates in the PBG at a group velocity of $0.34c$ only, which corresponds to 40% of the speed of light in the uniform plasma, i.e., no grating (NG) case.

The group-velocity dispersion (GVD) $\beta_2^g = d^2k/d\omega^2$ is found to be

$$\beta_2^g = -\frac{\mathrm{sgn}(\delta)\chi^2/v_{g0}^2}{(\delta^2 - \chi^2)^{3/2}}. \quad (6)$$

Eq. (6) indicates that on the lower branch ($\delta < -\chi$) of the band gap, the grating dispersion is *normal* ($\beta_2^g > 0$); on the upper branch ($\delta > \chi$), the dispersion is *anomalous*. Moreover, the grating dispersion approaches infinite at the band gap edges. For a signal light of $\omega = 0.9\omega_B$ propagating in the PBG given in Figure 1, for example, one obtains $\beta_2^g = 1.6 \times 10^4$ fs^2/mm, much larger than the GVD $\beta_2 \equiv -(c^2 v_g^3 \omega)(n/n_c) = 1.2 \times 10^3$ fs^2/mm in the uniform plasma, which is naturally anomalous. Therefore, the grating formation reverses the plasma medium dispersion from anomalous to normal on the lower branch of the band gap, and largely strengthens the anomalous dispersion on the upper branch. Owing to the strong dispersion, the PBG can be a novel dispersion element. Also one can obtain the third-order dispersion (TOD) $\beta_3^g = (3|\delta|\chi^2/v_{g0}^3)/(\delta^2 - \chi^2)^{5/2}$, which is always positive and becomes infinitely large at the band gap edges. The positive TOD induces fluctuant structures at the trailing edge of the light pulse (Agrawal, 1995). TOD is the main factor for limiting the pulse compression in the grating (Agrawal, 2001).

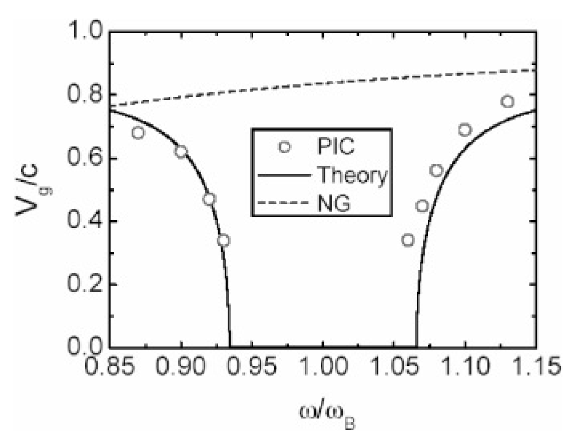

Fig. 3. Group velocity of the signal pulses around the photonic band gap. The group velocity in uniform plasma is also shown by the dashed line.

Figure 4 shows pulse stretching [(**a**) and (**b**)] and chirped-pulse compression [(**c**) and (**d**)] in the PBG given Figure 1. In both cases, the central frequency of the signal pulses is on the lower branch of the band gap, where the grating dispersion is normal. The incident pulses have the Gaussian envelope $a_0 \exp[-(1+iC)t^2/T_0^2]$, where C is the chirp factor. In the pulse stretching case, the incident pulse is with $C = 0$, $a_0 = 0.04$, and $T_0 = 10\tau_0$, which reaches the left boundary of the PBG at $t = 795\tau_0$. Figure 4a shows that the pulse is stretched faster when the light frequency is closer to the band gap edge ($\omega = 0.935\omega_B$). This is due to the increasing dispersion at the band gap edge as predicted by Eq. (6). For the NG case, the signal light of $\omega = 0.92\omega_B$ propagates through the uniform plasma almost with a constant duration, indicating a very small dispersion as compared with the PBG case. Figure 4b shows the output pulse at the right boundary for $\omega = 0.92\omega_B$. PIC simulation (solid line) is recovered by the coupled-mode theory (dashed line) by numerically solving Eqs. (2) and (3) (Sterke *et al.*, 1991), using $\delta n_1 \approx 0.13 n_c$ and $\delta n_2 \approx 0.08 n_c$ for the PBG as shown in Figure 1.

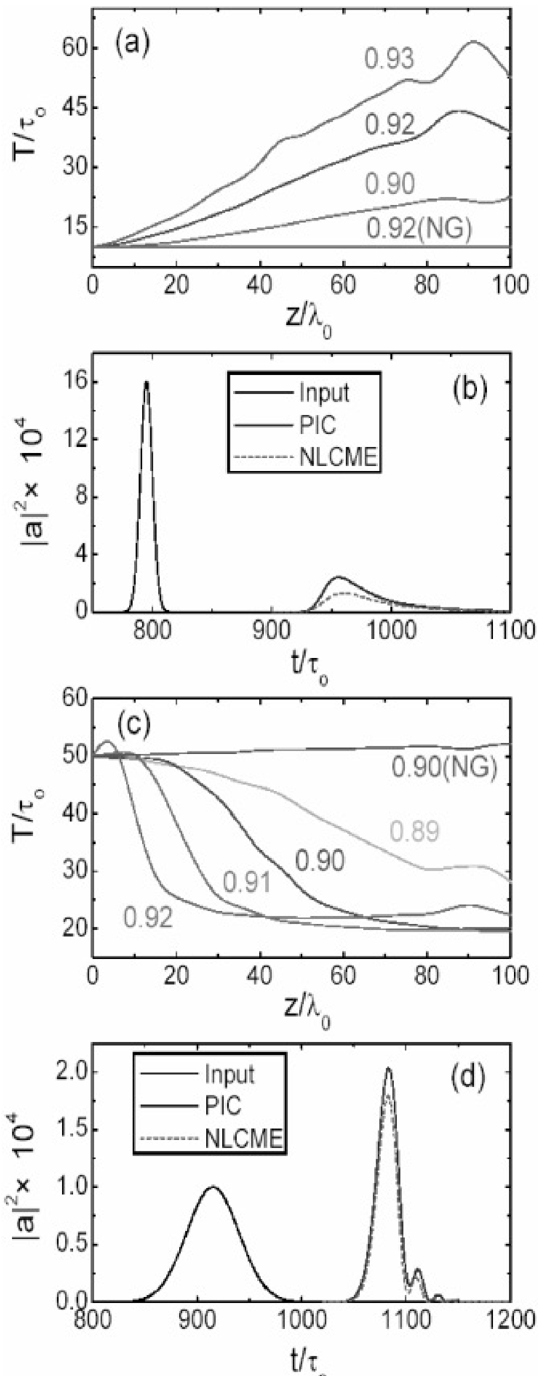

Fig. 4. (**a**) Pulse stretching as a function of the propagating distance because of PBG's strong dispersion. The numerical labels indicate the frequencies; (**b**) Stretched pulse shapes found from PIC simulation and model calculation for $\omega = 0.92\omega_B$; (**c**) Compression of chirped pulses as a function of the propagating distance because of PBG's strong dispersion. The numerical labels indicate the frequencies; (**d**) Compressed pulse shapes found from PIC simulation and model calculation for $\omega = 0.9\omega_B$.

In the case for chirped-pulse compression, the incident pulse has a negative chirp factor $C = -4$, an amplitude $a_0 = 0.01$, and a duration $T_0 = 50\tau_0$, which reaches the left boundary at $t = 915\tau_0$. As shown in Figure 4c, the chirped pulse is compressed faster when the light frequency is closer to the band gap edge. The reason is the same as for the pulse stretching. For the NG case, the signal light of $\omega = 0.9\omega_B$ is slightly stretched because of anomalous dispersion of the uniform plasma. The compression of the negatively chirped pulse indicates that here the grating dispersion is normal. Figure 4d shows the output pulse for $\omega = 0.9\omega_B$. Again the coupled-mode theory is well consistent with the PIC simulation. The little fluctuation at the trailing edge of the pulse is due to the TOD effect, as mentioned above.

Both pulse stretching and chirped-pulse compression are linear propagation in PBG. We also study the nonlinear propagation of weakly relativistic laser pulse in PBG (Wu *et al.*, 2005), and observe the compression of Bragg grating soliton (BGS) (Eggleton *et al.*, 1996, 1997; Agrawal, 2001). Eqs. (2) and (3) also qualitatively agree with the PIC simulation results. The BGS compression is much faster than the self-compression of the pulse in the uniform plasma (Shorokhov *et al.*, 2003). The fast BGS compression can be used to generate powerful laser pulses with the duration of about 10 femtosecond.

In conclusion, the propagation of the ultrashort intense laser pulses in a PBG induced by intersecting laser pulses was studied. The PBG shows an ultrawide photonic band gap, near which strong dispersion appears. Both theory and PIC simulations suggest that the PBG is a simple and novel element for light speed reduction, pulse stretching, chirped pulse compression, and fast compression of BGS (Wu *et al.*, 2005). Because of its ultrahigh DT, three orders higher than that of the ordinary optical elements, it opens a way to manipulate femtosecond laser pulses in the high intensity regime, and may have important applications in generating femtosecond HEPW laser pulse in the future HEPW lasers.

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