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DISAPPEARANCE OF TWO-PLASMON DECAY INSTABILITY IN PLASMAS PRODUCED BY ULTRASHORT LASER PULSES*

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Harmonic emission was studied from a plasma produced by ultrashort laser pulses. Unlike the harmonics from plasmas created by long (ns) laser pulses, the 3/2 harmonic emission was not observed in the interaction between plasmas and ultrashort laser pulses. A simple model is proposed to explain this phenomenon.

Keywords: ultrashort pulse lasers, harmonic generation
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I. INTRODUCTION

The two-plasmon decay (TPD) instability represents the resonant decay of a laser light into two electron plasma waves,[1−3] their frequency and wave-number match conditions are as follows:

$$\omega_0 = \omega_1 + \omega_2, \quad k_0 = k_1 + k_2,$$

where $\omega_0(k_0)$ is the laser frequency(wave number) and $\omega_1(k_1)$ and $\omega_2(k_2)$ are the frequencies(wave numbers) of the electron plasma waves.

The growth rate for TPD in an inhomogeneous plasma is given by Langdon and Lasinski:[4]

$$\gamma = \frac{k_0 \nu_{\rm os}}{4}\left(1 - \frac{10.3\nu_{\rm e}^2}{\omega_{\rm pe}\nu_{\rm os}}\right) - \frac{\omega_{\rm pe}}{k_\perp L},$$

where $k_\perp$ is the component of the wave number of plasmas in the direction of the E field of the incident light. $L = n(\mathrm{d}n/\mathrm{d}x)^{-1}$ is the scale length. For given plasma conditions (temperature and scale length) the growth is maximized when: $k_\perp \approx \dfrac{1.2\omega_{\rm pe}}{\nu_{\rm e}}(k_0 L)^{-1/2}$. The inhomogeneous threshold intensity for the TPD instability is[5]

$$\left(\frac{\nu_{\rm os}}{\nu_{\rm e}}\right)^2 \approx \frac{12}{k_0 L}.$$

The 3/2 harmonic is produced by the TPD of laser-plasma interaction at the quarter critical density surface. For this reason, the diagnostics for the 3/2 harmonic is an effective way to investigate the instability at the quarter critical density surface. For interactions between plasmas and long laser pulses, the TPD instability is inevitable. The intensity and conversion efficiency of 3/2 harmonic emission is affected by laser intensity, electron temperature of plasmas and the plasma scale length L. In long pulse duration, the intensity of 3/2 harmonic is proportional to the plasma scale length and inversely proportional to the electron temperature of the plasma. It is our wish in this paper to investigate the TPD instability in plasmas generated by ultrashort laser pulses.

II. EXPERIMENTAL

Experiments were carried out with a Ti:sapphire chirped pulse amplification(CPA) laser system operating at 800 nm at a repetition rate of 10Hz. The laser delivered 5 mJ energy in 150fs pulses. The laser beam was focused on solid targets with an f/5 lens. A microscope system with a second identical f/5 lens as an objective was used to image the focal spot distribution on a charge coupled device. Thus, the focal condition could be directly monitored and optimized. The corresponding focal diameter for an incident beam of 15 mm diameter was less than 20μm. The peak intensity on targets was estimated to be approximately $8 \times 10^{15}\mathrm{W\cdot cm^{-2}}$. The intensity was kept constant within the limits set by the energy fluctuations of the laser system.

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P-polarized laser pulses were incident at 45° from the target normal in a perpendicular plane. The targets used in our experiments were planar CH and Al target. The target surface was polished to ensure the roughness of the surface to be less than 1μm. The target was moved 50μm after each shot so that laser shots interact with a fresh surface. The target together with the focusing optics and the target mount was kept in a vacuum chamber.

It is very important to know the effects of scale length of the plasma on the two-plasmon decay. For some shots, a prepulse was used to create larger scale length plasma. The prepulse was introduced by a dog-leg system[6] with an 8% intensity of the main pulse and it arrived at the target surface 50ps earlier than the main laser pulse.[7,8]

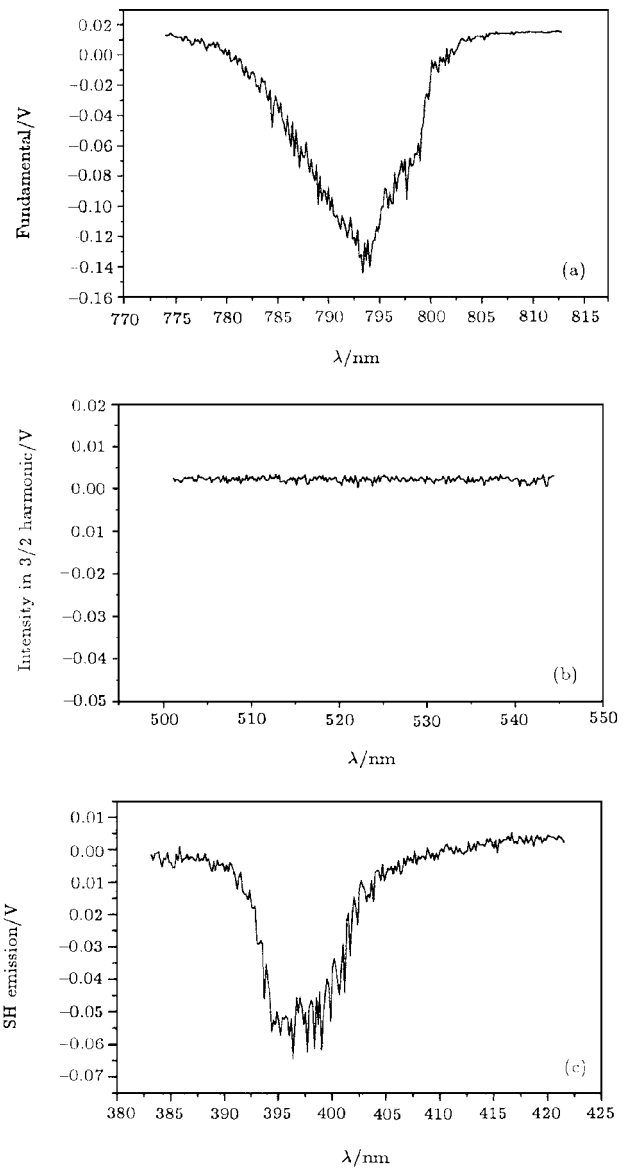


Fig.1. The scattering spectrum in $\omega_0, 3\omega_0/2$ and $2\omega_0$.

Scattered spectrum was collected by an f/3.75 quartz lens in the horizontal plane containing the axis of the incident laser, which was at about 45° from the normal of the target. The collection lens was aligned to produce an image onto the incident slit of a 0.5-m grating monochromator. The time-integrated spectrum of harmonics was spacially resolved by the monochromator coupled with a photomultiplier(R456).The data were recorded and processed by a signal detection and analysis system (EG&G Model 4420 Boxcar Averager/Model 4422 Gatal Integrator and Model 4402 Signal Processor), which was used to measure the scattered spectrum from laser-target interaction in the spectral range of 300 to 1000nm. This range includes $\omega_0, 3\omega_0/2$ and $2\omega_0$. The scattered spectrum of ω_0 and $2\omega_0$ can be seen clearly in Fig.1, while the $3/2\omega_0$ was absent under all conditions, including the change of the detecting angle from $-150°$ to $150°$ of k_0.

Al and CH target material was used to confirm this while the scale length of plasma was changed through our dog-leg system. But the result is the same: the $3\omega_0/2$ harmonic emission does not appear in plasmas produced by ultrashort laser pulses. In the following section, we shall discuss the causes for this disappearance.

III. MAIN RESULTS

When a powerful laser beam passes through plasmas, it expels electrons on its way and cause self-focusing, thus the variation of the electron density and the electron relativistic mass should be considered when we study the interaction between plasmas and ultrashort laser pulses. Now supposing a laser beam at frequency ω_0 is mixed with a plasma, the relevant equation for laser vector potential A[9] is

$$\left[\nabla_\perp^2 + \frac{1}{c^2}\partial_\xi\partial_{\overline{\xi}}\right] A = \omega_{\rm pe}^2 A, \tag{1}$$

where $\omega_{\rm pe}^2 = \dfrac{e^2}{m_{\rm e}}\dfrac{(n_i - \nabla_\perp^2)}{\gamma}, \gamma = \sqrt{1 + \dfrac{1}{m_{\rm e}^2 c^2} I}, \xi = z/c - t, \overline{\xi} = z/c + t$, in which the variation of both electronic density and electronic mass are included. Here, $n_{\rm i}$ is ionic density and $I = |A|^2$. For any wave, $A_{\omega,\overline{\omega}} = A^\perp_{\omega,\overline{\omega}} \exp(\mathrm{i}\omega\xi)\exp(\mathrm{i}\overline{\omega}\overline{\xi})$, we have

$$\begin{aligned} &-\nabla_\perp^2 A^\perp_{\omega,\overline{\omega}} + \omega_{\rm pe}^2 A^\perp_{\omega,\overline{\omega}} + \omega\overline{\omega} A^\perp_{\omega,\overline{\omega}} \\ &+ \mathrm{i}\omega\partial_{\overline{\xi}} A^\perp_{\omega,\overline{\omega}} + \mathrm{i}\overline{\omega}\partial_\xi A^\perp_{\omega,\overline{\omega}} = 0. \end{aligned} \tag{2}$$

For $\overline{\omega} = 0$ and $A \sim \exp(\mathrm{i}\omega t)$ case, i.e., monochromatic laser beam, there is

$$-\nabla_\perp^2 A^\perp_{\omega,0} + \omega_{\rm pe}^2 A^\perp_{\omega,0} = 0. \tag{3}$$

By solving Eq.(3), one can get beam the transverse structure, i.e., $I = |A^{\perp}|^2$ profile. Considering forward scattering effect, the beam becomes multicolor and hence we express A as a sum of various forward moving waves of respective color

$$A = \sum_{\mu,0} A_{\omega,0}[1 + \lambda_{(\mu,0)}\exp(\mathrm{i}\mu\xi)] = A_{\omega,0} + \sum_{\mu\neq 0} A_{\mu,0}, \tag{4}$$

$$A_{\mu,0} = \lambda_{(\mu=0,\overline{\mu}=0)} = 0. \tag{5}$$

For relativistic factor, there are

$$\gamma = \sqrt{1 + \frac{1}{m_e^2c^2}I} = \sqrt{1 + \frac{1}{m_e^2c^2}I^0 \times H}, \tag{6}$$

$$\begin{aligned} H =& 1 + \sum_{\mu}\lambda^2_{(\mu,0)} + 2\sum_{\mu}|\lambda_{(\mu,0)}|\cos(\mu\xi) \\ &+ 2\sum_{\mu_1}\sum_{\mu_2}\sqrt{\lambda_{(\mu_1,0)}\lambda_{(\mu_2,0)}} \\ &\cdot\cos[(\mu_1-\mu_2)\xi] = H_0 + H_1, \end{aligned} \tag{7}$$

where

$$H_0 = 1 + \sum_{\mu}\lambda^2_{(\mu,0)} + 2\sum_{\mu}|\lambda_{(\mu,0)}|\cos(\mu\xi), \tag{8}$$

$$H_1 = 2\sum_{\mu_1}\sum_{\mu_2}\sqrt{\lambda_{(\mu_1,0)}\lambda_{(\mu_2,0)}}\cos[(\mu_1-\mu_2)\xi], \tag{9}$$

$$\gamma_0 = \sqrt{1 + \frac{1}{m_e^2c^2}I^0}.$$

The change of γ, and hence ω_{pe}^2, will lead to the variation of beam transverse structure and transverse profile of electrons $n_i - \nabla_{\perp}^2\gamma$; in term of energy, it losses energy

$$\frac{1}{2}\omega_{pe}^2(\gamma)|A|^2 - \frac{1}{2}\omega_{pe}^2(\gamma_0)|A_0|^2,$$

i.e., the increase of electron quiver energy obtained from the laser field. Here, the transverse structure of the fundamental beam $A_{\omega,0}$ is the most stable one. The one related to the electron quiver energy is the lowest and its relativistic factor is γ_0. Due to the high beam intensity, such an energy loss is significant. However, there exists a special type of scattering which keeps $\gamma = \gamma_0$:

$$\lambda^2 + 2|\lambda|\cos(\mu\xi) = 0,$$

$$\begin{aligned} \lambda &= |\cos(\mu\xi)| - \cos(\mu\xi) \\ &= \begin{cases} 0, & 2k\pi - \pi/2 < \mu\xi < 2k\pi + \pi/2, \\ 2\cos(\mu\xi), & 2k\pi + \pi/2 < \mu\xi < 2k\pi + 3\pi/2. \end{cases} \end{aligned}$$

Here, the dependence of γ on H_i, the interference between scattered waves of different frequency-shift, is neglected. Thus for this type of scattering, the transverse structure of beam is not changed. Clearly, this type of scattering is energetically more favorable than other types of non-zero energy loss.

The scattered spectrum for different ξ shows a comb structure and $\mu = 0$ is always located in gaps. The central gap for the case of $\xi = \infty$ can be taken as zero-width in gaps. By contrast, the central gap for the case of $\xi = 0$ can be regarded as of infinite-width. An integrated scattered-spectrum, obtained by summation of spectra over pulse duration $(-\tau, \tau)$, exhibits all possible frequency-shift modes in this pulse-duration. After integration, non-central gaps in the respective spectrum will be partially filled, but a central gap will remain due to finite pulse duration. The existence of the central gap suggests that some frequency-shift modes are prohibited in Fig.2. The central gap begins from $-\pi/2\tau$ and ends at $\pi/2\tau$. The width of the central gap is inversely proportional to the pulse duration (see Fig.3). Thus for ultrashort pulses, the signal at some frequency is absent due to the central gap, whereas for long pulse duration, this frequency will sweep into side-peak. For example, as for the laser beam we used, half pulse duration τ=75fs and frequency $\omega_0 = 2\pi c/\lambda = 2.36 \times 10^{13}\mathrm{s}^{-1}$, the boundary of the central gap is $\Delta\omega_g = 2.09 \times 10^{13}\mathrm{s}^{-1}$ and thus frequency-shift for $3\omega_0/2$ is $\Delta\omega = 3\omega_0/2 - \omega_0 = 1.18 \times 10^{13}\mathrm{s}^{-1} < \Delta\omega_g$. It is located in the central gap. Therefore, the scattered light of $3\omega_0/2$ cannot be detected. But for the scattered light of $2\omega_0$, the frequency-shift is greater than $\Delta\omega_g$, thus the $2\omega_0$ scattered light can be detected.

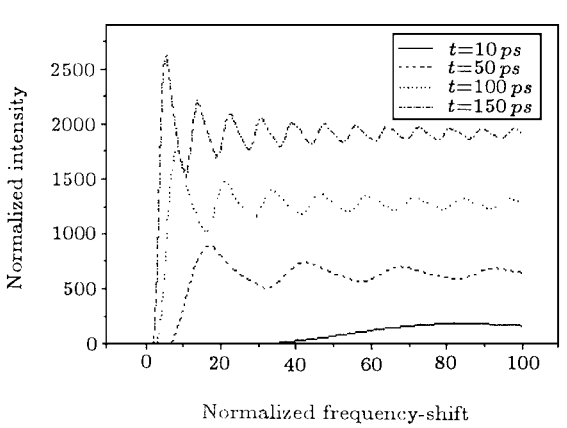


Fig.2. Scattered spectrum intensity vs frequency shift in different pulse durations.

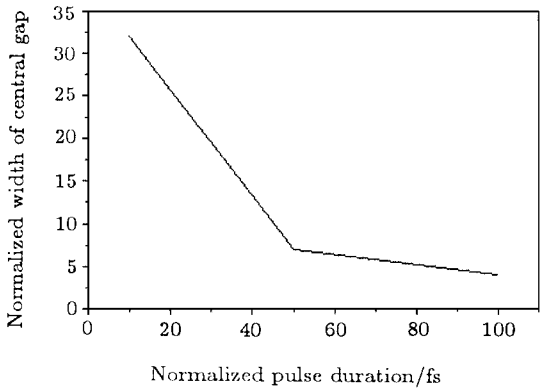


Fig.3. Plot of the gap width vs pulse duration.

From Fig.2, we can get another important conclusion: The intensity of harmonic emission is proportional to the pulse duration under the same laser intensity.

IV.CONCLUSION

In summary, harmonic emission was studied experimentally from a plasma produced by ultrashort laser pulses. Unlike the harmonics from plasmas created by long (ns) laser pulses, the 3/2 harmonic was not observed in the interaction between plasmas and ultrashort laser pulses. Changing the experimental conditions such as scale length of plasmas and the target material, we demonstrated the disappearance of the two-plasmon decay instability. To explain this disappearance, a simple model is proposed, which shows that there is a central gap in the scattered spectrum of frequency-shift and the gap width is changed by the laser pulse duration. Under our experimental conditions, the $3\omega_0/2$ is located in the central gap in the scattered spectrum.

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