HARMONIC GENERATION FROM A FEMTOSECOND LASER PRODUCED SOLID SURFACE PLASMA BY VARIATIONS OF ELECTRON DENSITY GRADIENT

H. Kuroda, R. A. Ganeev*, T. Kanai, A. Ishizawa, and T. Ozaki**

Institute for Solid State Physics, University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa, Chiba 277-8581, JAPAN
kuroda@issp.u-tokyo.ac.jp
* *permanent address - NPO Akadempribor, Academy of Sciences of Uzbekistan, Tashkent 700143, Uzbekistan*
** *present address - NTT Basic Research Laboratories, NTT Corporation, 3-1, Morinosato Wakamiya, Atsugi-shi, Kanagawa pref., 243-0198 Japan*

Abstract: Harmonic generation from solid surface plasmas is studied using a 500 fs pulse length Nd:Glass laser system. For a 45° angle of incidence, the specular up to the fifth harmonics are blueshifted when the laser intensity exceeds 2 x 10^{16} Wcm^{-2}. The second harmonic is blueshifted by about 16 Å, and the fifth harmonic is blueshifted by about 51 Å for p-polarization at the intensity of 1 x 10^{17} Wcm^{-2}. The blueshift is interpreted as the collisionless absorption due to the anomalous skin effect.

1. Introduction

The recent availability of compact, high-intensity subpicosecond lasers with chirped pulse amplification (CPA) [1] has opened the new field of study of laser-matter interactions with solid targets. With the recent advent of subpicosecond pulse length and high intensity laser, the absorption of light near the critical density again becomes an important subject of investigation. Very short density gradient scale length L/λ <<1, where λ is the laser wavelength, can be formed because there is no time for the free electron to expand into the vacuum region. We define the electron density gradient scale length L as the inverse of the logarithmic derivative $[(1/n_e)(dn_e/dx)]^{-1}$, where n_e is the upper shelf density [2]. It becomes important to investigate several additional absorption mechanisms for short pulse length and high intensity laser pulse interacting with overdense plasmas. At the high laser intensities above 10^{16} Wcm^{-2}, the electron temperature is more than one keV and the main laser absorption is related to collisionless absorption. Recently, Hansen et al. reported for the first time that the second harmonic is blueshifted when the laser intensity exceeds 5 x 10^{16} Wcm^{-2} and this effect is also observed in particle-in-cell (PIC) simulations [3]. They also reported that the blueshift is due to the absorption by the anomalous skin effect. However, no detailed study of the blueshifts in the other harmonic orders harmonics, nor the dependence on the laser intensity at the incidence angle of 45° has yet been reported. It is, therefore, timely to study the absorption mechanism in subpicosecond high intensity laser-plasma interaction.

In this paper we present blueshifts of up to 20 Å in the second harmonic and for the first time in our experimental condition 50 Å in the fifth harmonic by the irradiation of a solid target with 500 fs laser pulse for p-polarization and an incident angle of 45° and laser intensities above 3 x 10^{16} Wcm^{-2}. We carry out more detailed model-calculations of the electron temperature in our experimental condition using a 1D hydrodynamic code HYADES [4]. We find that the blueshift in our experiment can be well explained from the absorption mechanism due to the anomalous skin effect.

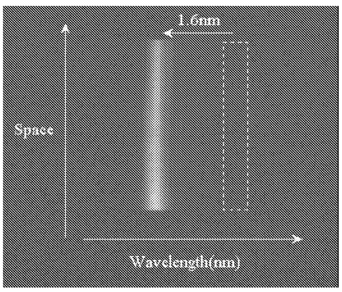
2. Experimental setup

We carried out experiments by using chirped pulse amplification (CPA) Nd:Glass laser system operating at a wavelength around 1060 nm and at repetition rate of one shot in each five minutes. The contrast ratio of each pulse is better than 10^{-8}. The laser delivered 100 mJ energy in 500 fs pulse and produced a peak intensity on the target of 2 x 10^{17} Wcm^{-2} at a laser focus of 12 μm diameter placed in the vacuum chamber. The laser pulse is point focused onto an Al deposited target within a vacuum chamber by using a 10 cm focal length achromatic lens. The incidence angle of the laser is 45° , the polarization of the driving laser is s- or p-polarized, and harmonics generated from the plasma surface in the specular direction are spectrally dispersed by a monochromater and detected using a CCD camera and a fast rise time photomultiplier.

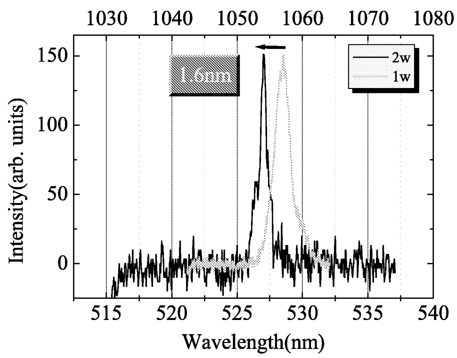
3. Results and discussion

It is very important that we investigate the spectral and spatial analysis of harmonics to understand the information on the critical density surface and overdense plasmas surface when the incidence laser interact with the plasma. As is well known, the resonance absorption process is dominant when incidence laser intensity is under 1 x 10^{16} Wcm^{-2}. If the resonance absorption process is dominant, harmonic frequency is not shifted except for Doppler shifts of reflected light arising from plasma expansion driven by the heated electrons [5, 6]. We can measure the Doppler shift in the reflected 1060 nm. The fundamental is blueshifted by about 6 Å corresponding to an expansion velocity $c_s/c \sim 4 \times 10^{-4}$.

Figure 1 summarizes the results of the second harmonic. The results is inconsistent with the resonant absorption: (1) the second harmonic light is blueshifted by about 16 Å (see Fig. 1(a), (b)) for p-polarization and the second harmonic signal for p-polarization is about 8 times higher than that for s-polarization at the fundamental laser intensity of $\sim 10^{17}$ Wcm^{-2}. (2) The dependence of the wavelength shift on the incidence laser intensity is shown in Fig. 2.



(a)



(b)

Fig. 1. Summary of the second harmonic: (a) The picture of the second harmonic and the dash line is the position of twice frequency of the fundamental laser. (b) The second harmonic spectrum (black line) and the incident laser spectrum (gray line) at the laser intensity of 1.5 x 10^{17} Wcm^{-2}.

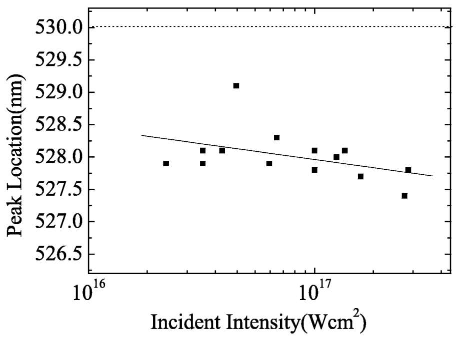


Fig. 2. Location of the second harmonic peak as a function of incident intensity.

The peak frequency of the second harmonic emission is blueshifted for $I_L \geqq 2 \times 10^{16}$ Wcm^{-2}, where I_L is the incidence laser intensity. It is found that the increase of this shift, with an increase in the laser intensity, is small in comparison with the experimental results by Hansen et al. [3]. The peak frequency of the third, fourth, and fifth harmonic emission is also blueshifted. The fifth harmonic light is blueshifted by about 51 Å for p-polarization at the intensity of $I_L \geqq 1 \times 10^{17}$ Wcm^{-2}. These blueshifts of the second and fifth harmonics are much larger in magnitude than the Doppler shift seen in the spectrum of the fundamental. These results cannot be explained by the hydrodynamic motion of plasma. With increasing laser intensity and electron temperature the role of collisions decrease and collisionless mechanisms of absorption become dominant [7, 8]. The experimental and particle-in-cell (PIC) simulation results by Hansen et al. [3] shows that the second harmonic due to collisionless absorption occurs when the laser intensity exceeds 5×10^{16} Wcm^{-2}. The calculation results by Rozmus et al. [7] show that at low temperature ($T_e <$ 300 eV), the collision absorption mechanism is dominant, and at higher temperature ($T_e >$ 800 eV), the collisionless absorption mechanism due to the anomalous skin effect becomes dominant. The electronic temperature profile in our experiment condition was calculated using a 1D hydrodynamic code HYADES [4]. Figure 3 shows the electron temperature profile for our experimental conditions when the main pulse laser intensity on the solid target is 1×10^{17} Wcm^{-2}. We can see from this figure that the electron temperature in the skin depth from the solid surface is much higher than 800 eV.

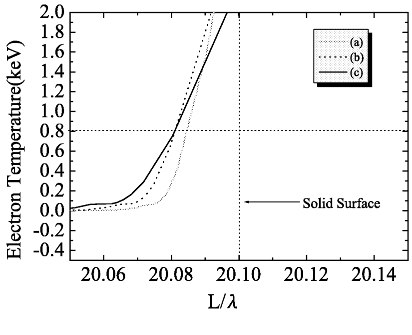


Fig. 3 The electron temperature for our experimental condition obtained from 1D HYADES code at the time (a) 200 fs, (b) 100 fs before the peak of laser pulse and (c) at the same time of the peak of laser pulse at the incident laser intensity of 1×10^{17} Wcm^{-2}.

The calculation results by Rozmus et al. [7] show that at the higher temperature (> 800 eV) the absorption is collisionless mechanism. Therefore, we can assume that from our experimental and calculation results the harmonic frequency shift is due to the collisionless mechanism. Hansen et al. also reported that if the frequency of the oscillation changed with its amplitude, then the applied electromagnetic field would drive the oscillation out of resonance. This can change the frequency of the radiation emitted by the moving charges involved. The phase between the 2nd and 5th harmonic should be different. There is a possibility that the difference in the wavelength shift between the orders of harmonics in our experimental results is attributed to the phase shift accumulation or phase shift oscillation. In an upcoming paper, we will report a more detailed analysis of the experimental data of other order harmonics.

4. Conclusion

Investigations have been performed on the harmonic generation from solid surface plasmas using the subpicosecond Nd:Glass lasers, and several new and interesting phenomena has been observed. The blueshift of the harmonics by collisionless process has been observed.

5. References

[1] M. D. Perry and G. Mourou, "Terawatt to Petawatt Subpicosecond Lasers," Science **264**, 917-924 (1994).

[2] S. Bastiani, A. Rousse, J. P. Geindre, P. Audebert, C. Quoix, G. Hamoniaux, A. Antonetti, and J. -C. Gauthier, "Experimental study of the interaction of subpicosecond laser pulses with solid targets of varying initial scale lengths," Phys. Rev. E **56**, 7179-7185 (1997).

[3] C. T. Hansen, S. C. Wilks, and P. E. Young, "Spatial Evidence for Collisionless Absorption in Subpicosecond Laser-Solid interactions," Phys. Rev. Lett. **83**, 5019-5022 (1999).

[4] A. M. Rubenchik, M. D. Feit, M. D. Perry, J. T. Larsen, "Numerical simulation of ultra-short laser pulse energy deposition and bulk transport for material processing," Appl. Surf. Sci. **129**, 193-198 (1998).

[5] H. M. Milchberg and R. R. Freeman, "Expansion-induced Doppler shifts from ultrashort-pulse laser-produced plasmas," Phys. Rev. A **41**, 2211-2214 (1990).

[6] O. L. Landen and W. E. Alley, "Dynamics of picosecond-laser-pulse plasmas determined from the spectral shifts of reflected probe pulses," Phys. Rev. A **46**, 5089-5100 (1992).

[7] W. Rozmus, V. T. Tikhonchuk, and R. Cauble, "A model of ultrashort laser pulse absorption in solid targets," Phys. Plasmas **3**, 360-367 (1996).

[8] S. C. Wilks and W. L. Kruer, "Absorption of Ultrashort, Ultra-Intense Laser Light by Solids and Overdense Plasmas," IEEE J. Quantum Electron. **33**, 1954-1968 (1997).

6. Acknowledgments

This research was partially supported by the Ministry of Education, Culture, Sports, Science and Technology, Grant-in-Aid for 11308014 and JSPS Fellows, 08916, 2000. R. A. Ganeev would like to acknowledge the Ministry of Education, Culture, Sports, Science and Technology for providing financial support during his stay with the ISSP through the program COE Research Fellowship.