Physics Letters A ••• (••••) •••–•••

Contents lists available at ScienceDirect

Physics Letters A

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Mechanism of equivalent electric dipole oscillation for high-order harmonic generation from grating-structured solid-surface by femtosecond laser pulse

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ARTICLE INFO

Article history:
Received 19 September 2016
Received in revised form 26 March 2017
Accepted 22 April 2017
Available online xxxx
Communicated by F. Porcelli

Keywords:
HHG
Gratings
Plasmas
Particle-in-cell

ABSTRACT

We theoretically study high-order harmonic generation (HHG) from relativistically driven overdense plasma targets with rectangularly grating-structured surfaces by femtosecond laser pulses. Our particle-in-cell (PIC) simulations show that, under the conditions of low laser intensity and plasma density, the harmonics emit principally along small angles deviating from the target surface. Further investigation of the surface electron dynamics reveals that the electron bunches are formed by the interaction between the laser field and the target surface, giving rise to the oscillation of equivalent electric-dipole (OEED), which enhances specific harmonic orders. Our work helps understand the mechanism of harmonic emissions from grating targets and the distinction from the planar harmonic scheme.

1. Introduction

High-order harmonic generation (HHG) by intense ultrashort laser pulses impinging solid targets is of great potential to produce bright coherent radiations, such as extreme-ultraviolet (EUV), soft X-ray radiations and attosecond pulses [1]. So far HHG induced by laser–plasma interaction for planar-targets has been extensively studied both theoretically and experimentally [2], through which two fundamental mechanisms, i.e., relativistic oscillating mirror [3,4] and coherent wakefield emission [5] are presented. The former attributes HHG to the reflection from collective relativistic plasma oscillations driven by relativistic laser pulses near the critical surfaces, and the latter proposes that the origin is the longitudinal motion of *Brunel* electron bunches [6] in the density gradient region.

Recently a new scheme [7] for HHG induced directly by an intense femtosecond laser irradiating grating-structured solid surfaces has been performed to generate more brighter harmonic emission. Compared with that by the planar-target scheme, the numerical simulations indicate that some enhanced special orders of harmonics appear nearly parallel to the target surface (near-surface) and the spectral components are strongly dependent on the grating periodicity. Such phenomena have been confirmed experimentally by a grating-structured target with sinusoidal modulations [8]. Further theoretical works interpreted it is due to the contribution of relativistic electron bunches emanating from each grating protuberance, giving rise to constructive interference with harmonic radiating fields of the same orders [9]. A latest report considers it as the role of the relativistic surface plasmon-driven enhancement [10]. These indeed satisfactorily explain the enhancement of coherent emission of harmonics in some special orders, especially in high-intensity case. However, why this constructive interference of harmonic radiation appears only at small angles and markedly in the weak-intensity case, is still not well understood.

By means of 2D PIC simulations, in this letter, we examine the angle distributions of harmonic emissions from grating-structured solid surfaces, impinged normally by both strong (2×10^{20} W/cm^2) and weak (8.6×10^{18} W/cm^2) laser pulses. The results show that, besides the well-known near-surface emissions, there exist other considerable harmonic distributions in large angles deviated from grating surfaces even in the case of weaker intensity. Based on these harmonic features, we propose a feasible emission mechanism: the oscillation of equivalent electric-dipole (OEED). In the present model, transient electric-dipoles are formed by the oscillating electron bunches and immobile surface-ions, the OEED gives rise to transient dipole radiations, by which the angle distributions and the enhanced harmonic orders can be interpreted self-consistently.

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http://dx.doi.org/10.1016/j.physleta.2017.04.034
0375-9601/© 2017 Published by Elsevier B.V.

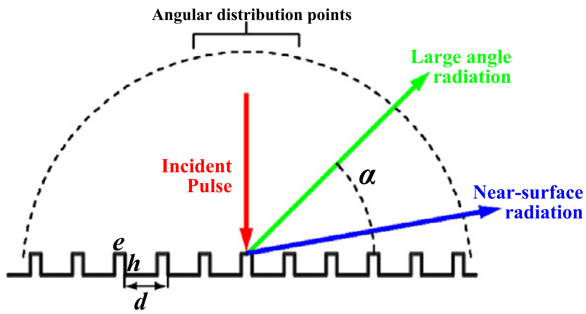

Fig. 1. Schematic of simulations. The dashed semicircle is used to guide the angular distributions of the harmonic intensities.

2. PIC simulation scheme

Our simulations are based on the code VSim working in 2D mode [11]. As shown in Fig. 1, the plasma particles are arranged in a grating profile with rectangularly-shaped protuberances (RSPs), with periodicity $d = (1/4)\lambda_0$, width $e = (1/16)\lambda_0$ and height $h = (1/8)\lambda_0$. The wavelength of the incident laser λ_0 is chosen at 400 nm, and the polarization is perpendicular to the grooves. The wave-front of the incident pulses is treated as flat. The transverse and the temporal profiles are all Gaussian forms, with beam width and pulse duration at 1.6 μm ($4\lambda_0$) and 10.4 fs ($8\,T_L$, T_L is the period of the incident light), respectively. The cell width is set at $DX = DY = \lambda_0/160$, and the number of macroparticles in each cell is 30. Dimensionless laser vector potential $a_0 = eE_0/cm\omega_0$ is equal to 1 and 5 in each case. It is well-known that in harmonic generation theories, the parameter $S = N_e/a_0N_c$ plays an important role [12], where N_e and N_c correspond to plasma density and critical plasma density, respectively. Compared to the planar-target scheme, S has much more critical effects for grating structures [9]. We find that matching S to 4 can greatly enhance the harmonic efficiency, thus the plasma density is set to $4N_c$ and $20N_c$ in our simulations.

3. Results of harmonic spectrums

Fig. 2 shows the results of harmonic spectra generated from the grating targets. In the case of $a_0 = 1$ ($N_e = 4N_c$) in Fig. 2(a) and 2(b), harmonics along the small angle (5°) with their harmonic orders $n = \omega/\omega_0$ at 4, 8, 12, 16, and 20 obviously stand out, which surpass the adjacent harmonics in intensity by tens of times. This is consistent with the result for $a_0 = 5$ ($N_e = 20N_c$), as shown by the blue line in Fig. 2(c). The orders of the enhanced harmonics also agree with the expectation from the constructive interference model [9]. In Fig. 2(a) and 2(c), the intensities of the enhanced harmonics at 5° surpass that of the reflection direction (90°) by more than one order of magnitude, and the intensity difference becomes much larger for strong incident laser ($a_0 = 5$). Compared with HHG at 90° from a planar target, the intensity of 4th harmonic from a grating target surface is suppressed, while intensities of 8, 12, 16th harmonics are only slightly stronger for $a_0 = 1$, as shown in Fig. 2(b). However, as shown in Fig. 2(d), harmonic intensities at $a_0 = 5$ from a grating target at 5° exceeds that from a planar target at 90° direction by 20 times (12th) and 50 times (16th), while low-order harmonics (4th and 8th) are still slightly weaker. Thus we can conclude, with the same interaction conditions, (1) using grating-structured surfaces can effectively generate higher intense harmonic radiation, especially for higher harmonic orders; (2) increasing the intensity of the incident pulses ($S = N_e/a_0N_c \approx 4$) can significantly enhance the harmonic intensities at small angles from grating targets. Therefore, for the purpose of generating bright harmonic radiation, the grating-target scheme is more beneficial than the planar-target scheme, and such a advantage is more prominent with strong incident pulses.

4. Harmonic angular distribution of grating-target

Figs. 3(a) and 3(b) show the angular distributions of the harmonic intensities at $a_0 = 1$ and 5, since the intensity is symmetric under the normal incidence, we only present the distributions from 0° to 90°. The harmonic emission angles are calculated using the interference model $d(\cos\alpha - \sin\theta_i) = k\lambda_L/n$ [9], where

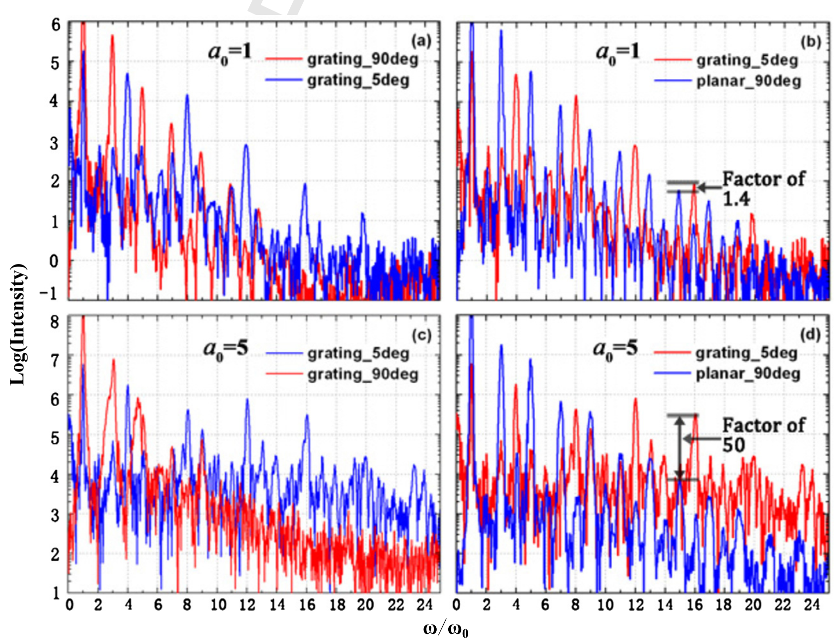

Fig. 2. Harmonic spectra generated from grating and planar targets at normal incidence. (a) Harmonic radiations at 5° (the blue line) and 90° (the red line) from a grating target, by weak incident pulses $a_0 = 1$, $N_e = 4N_c$. (b) Comparison between harmonic spectra from a grating target at observation angle 5° (the red line) and a planar target at 90° (the blue line). (c) and (d) Harmonic radiations from both targets, by strong incident pulses, with incident intensity and plasma density changed to $a_0 = 5$ and $N_e = 20N_c$. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)