Circularly-Polarized Harmonic Generation in Underdense Plasma Using Bi-Color Lasers

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Abstract: We have modeled bi-color circularly polarized harmonic generation in underdense plasmas using a combination of PIC simulation and a nonlinear fluid model. Generalized selection rules and helicities, together with harmonic efficiencies are predicted and found to be consistent with numerical results.

1. Introduction

Circularly-polarized (CP) extreme UV- and X-ray radiation is an essential tool for analyzing the magnetic properties of materials. Recently, CP harmonic generation in gas has experimentally been observed by Kfir *et al.* [1] using two CP laser pulses with different frequencies ($400 + 800nm$ wavelength). Subsequently Chen *et al.* [3] investigated CP bi-color harmonic generation on the a thin overdense plasma slab using particle-in-cell simulation and reported analogous selection rules as in [1]. Sharma *et al.* analytically determined the selection rules and efficiencies up to the 5th harmonic in underdense plasma [4]. Here we model bi-color CP harmonics for arbitrary order under similar conditions [5]. Our study offers new physical insight into this process and represents an important first step in extending the potential wavelength range and brightness of CP HHG in plasmas by avoiding the ionization limit inherent from gaseous media which prevents the use of extremely high laser intensities.

2. Fluid Model Results

We have developed a 1D fluid model using dispersion free Directional Splitting (DS) field solver [2] combined with a fully nonlinear description of the plasma wave response to the laser ponderomotive force. According to this model, harmonics generated by two counter-polarized pulses $\mathbf{A}_1 = (0, A_0/\sqrt{2}\cos\theta, A_0/\sqrt{2}\sin\theta)$ and $\mathbf{A}_2 = (0, A_0'/\sqrt{2}\cos\theta', -A_0'/\sqrt{2}\sin\theta')$ with arbitrary amplitude are always circularly polarized, with $\theta = \omega_0 t - k_0 x$ and $\theta' = q\omega_0 t + k_q x$ and q the frequency ratio of the two pulses. It is shown that harmonics $(q+1)m+1$ are left circularly polarized (LCP), whereas harmonics $(q+1)m-1$ are right circularly polarized. Figure 1 illustrates the harmonic spectra for different pump frequency ratios $q = 2,3,4$. As can be seen, for $q = 2$ only $3m\pm1$, for $q = 3$ only $4m\pm1$, and for $q = 4$ only $5m\pm1$ harmonics exist. A semi-analytical model based on a quasi-linear theory

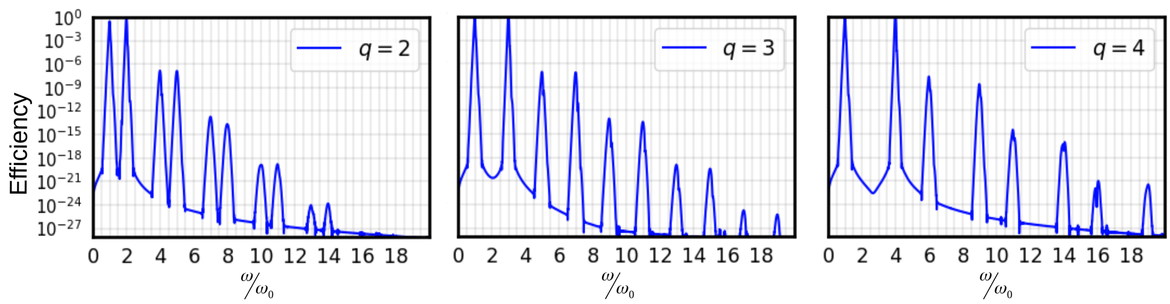

Fig. 1. Harmonic power efficiencies computed from fluid model using bi-color CP pulses with three different frequency ratios. The simulation is done for total laser intensity of $I = 10^{18}\,W/cm^2$ $(I_{2\omega_0}/I_{2\omega_0} = 2)$ and target density of $n_e = 0.05n_c$

yields a power scaling law for LCP and RCP harmonics, respectively of:

$$\frac{P^{LCP}_{(q+1)m+1}}{P_0} \approx \left(\frac{(q+1)m+1}{2^{6m+5}(q+1)^2}\right)^2 \left(\frac{(2m)!}{m!!}\right)^2 \left(\frac{\omega_p}{\omega_0}\right)^{4m} \frac{A_0^{2m+2}A_0'^{2m}}{(A_0^2+q^2A_0'^2)\gamma_0^{6m}} \tag{1}$$

$$\frac{P^{RCP}_{(q+1)m-1}}{P_0} \approx \left(\frac{(q+1)m+q}{2^{6m+5}(q+1)^2}\right)^2 \left(\frac{(2m)!}{m!!}\right)^2 \left(\frac{\omega_p}{\omega_0}\right)^{4m} \frac{A_0^{2m}A_0'^{2m+2}}{(A_0^2+q^2A_0'^2)\gamma_0^{6m}} \tag{2}$$

Comparison of the fluid model results with 1D PIC simulation using EPOCH code [6] show generally good agreement with departures at higher densities which can be traced to the onset of parametric instabilities such as forward Raman scattering. However, selection rules are completely consistent with the fluid model, showing generation of every $(q+1)m \pm 1$ harmonics. In contrast to the symmetry arguments invoked in Ref. [3], it is shown that harmonic selection arises naturally by examining the contributions to the nonlinear current source.

3. Free Electron Trajectory

CP harmonics in gas are generated as a result of electron recombination with the atoms. Using a single CP pulse there will be no harmonic generated since electrons do not return to their origin. The same holds for plasmas; harmonic generation is suppressed when using a single CP pulse due to constant energy of electrons on a circular orbit. However, using electron trajectories for different ratio of the laser pulses we have shown higher harmonics are generated even though the electron does not necessarily return to their original position. Although the selection rules are the same, the underlying mechanism is physically distinct for CP harmonic in gases and plasmas. Figure 2 shows example single electron trajectories and electric field structures for two different laser intensity ratios of $I_{2\omega_0}/I_{\omega_0} = 16$ and $I_{2\omega_0}/I_{\omega_0} = 0.25$ where in neither of the cases does the electron return to its original point in a cycle. Instead, acceleration and deceleration of electrons in a cycle leads to emission of photons, Fig. 2(b),(d). Indeed, there is only one specific laser ratio, $I_{2\omega_0}/I_{\omega_0} = 16$ where the electron returns back to its origin three times (for $q = 2$) in a cycle.

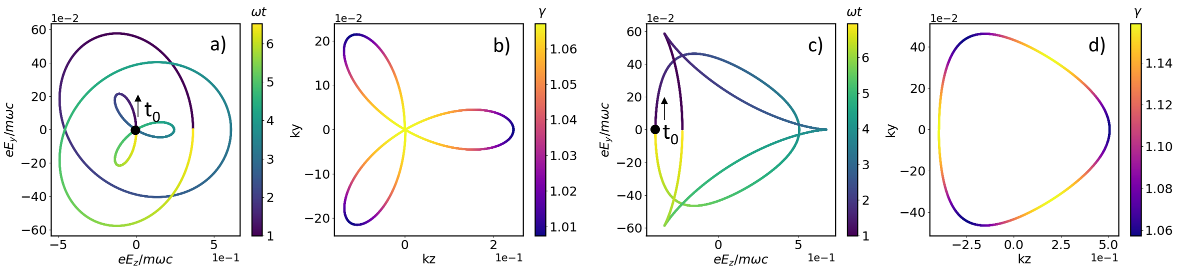

Fig. 2. Fluid model results of single electron trajectory for a,b) laser intensity ratio of $I_{2\omega_0}/I_{2\omega_0} = 16$ and c,d) $I_{2\omega_0}/I_{2\omega_0} = 0.25$. (a) and (c) show the electric superposition of electric fields of the lasers and the initial time is marked in the electron orbit, with color showing the time. (b) and (d) show the electron orbit with color showing the the relativistic Lorentz factor γ.

References

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