Plasma Mirrors for Generating Co- and Counter-Rotating Harmonics

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Abstract: We show that plasma mirrors driven by elliptically polarized laser beams emit harmonics that either co- or counter-rotate with the reflected fundamental, depending on the polarization state of the driving laser.

1. Introduction

The polarization state of emitted harmonics from plasma mirrors are governed by a set of selection rules which predict the polarization state of radiated harmonics when given the polarization state of the driving laser [1]. Most previous work utilized P-polarized driving lasers since they offer the most efficient conversion efficiencies [2-4]. However, several works have reported on the prospect of achieving a polarization-controlled harmonic source from plasma mirrors by tuning the ellipticity of a single driving laser [5-7]. In this work, we investigate the ellipticity of harmonics radiated from plasma mirrors driven by single-color, elliptically polarized lasers. First, we show that tuning the driving laser's ellipticity yields two regimes in which nearly circularly polarized (CP) harmonics can be generated. The first is when the driving laser is nearly CP polarized, for which the emitted harmonics co-rotate with the reflected fundamental, and the second is when the driving laser is nearly S-polarized, for which the emitted harmonics counter-rotate with the reflected fundamental. Particle-in-cell simulations are used to illustrate the electron bunch dynamics leading up the emission of the harmonics.

2. Circularly Polarized Harmonics from Relativistically-Driven Plasma Mirrors

In Fig. 1(a), the relative fraction of energy contained in the S and P components of the reflected harmonics is plotted as a function of the energy contained in the S-polarized component of the driving laser, I_s/I_L. For odd-ordered harmonics, the fraction of energy contained in the S-polarized component experiences a monotonic increase from purely P-polarized to purely S-polarized, in conjunction with the incident driving laser. For even ordered harmonics, the fraction of energy contained in the S-polarized component first increases together with odd-ordered harmonics, but eventually peaks and rapidly drops to -1 in agreement with the selection rules of harmonic generation which predicts P-polarized odd harmonics and S-polarized even harmonics for S-polarized driving lasers. For CP harmonics we desire equal amounts of energy in the S and P polarized components, which is one criteria for CP harmonics. For odd harmonics, this happens only once when the driving laser is CP, but for even harmonics this happens twice: once when the driving laser is CP and again when the laser is nearly S-polarized.

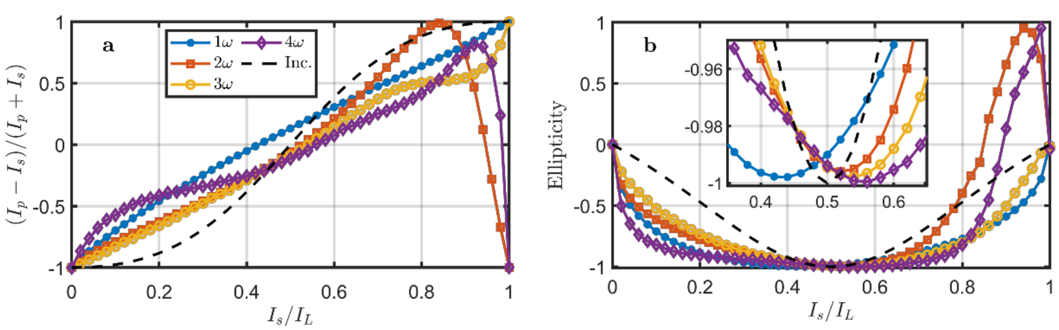

Figure 1: Two-dimensional particle-in-cell simulations characterizing the polarization state of the reflected harmonics as a function of the fraction of energy contained in the S-polarized component of the driving laser, I_s/I_L. (a) Relative fraction of energy between the P-polarized and S-polarized component for the first four reflected harmonics. (b) is the same as (a) except that the y-axis measures the ellipticity of the reflected beam. Simulation parameters: $a_0 = 10$, $N = 400$, $\theta = 45$ º, $\tau/TL = 8$, $Wo/\lambda_L = 4$, $L = 0.05$, I_s/I_L = varied, $\varphi_{sp} = \pi/2$, $\lambda_L/\Delta x = \lambda_L/\Delta y = 280$, and particles/cell = 7.

In Fig. 1b, the ellipticity is plotted as a function of I_s/I_L. When $I_s/I_L = 0.5$, all harmonic orders have an ellipticity close to -1, which is the same as that of the reflected fundamental. In contrast, for $I_s/I_L > 0.90$, the even ordered harmonics and superposition of high-order harmonics reach a maximum ellipticity close to 1, which is an opposite orientation to the reflected fundamental. Therefore, while interactions with $I_s/I_L = 0.5$ produce harmonics which co-rotate with the reflected fundamental, those with $I_s/I_L > 0.90$ produce harmonics which counter-rotate with the reflected fundamental.

3. Electron Bunch Dynamics and Attosecond Pulse Emission

To gain insight into this phenomenon we investigate the plasma dynamics leading up to the emission of the attosecond pulses. Fig. 2 plots the emitted attosecond pulses (a-c) and space-time density contours (d-f) for the cases when I_s/I_L = 1.0, 0.99, and 0.5. For these figures, only a few cycles near the central envelope are shown. For I_s/I_L = 1.0, we observe the emission of an attosecond pulse train with half-period spacing in which all attosecond pulses are nearly CP, in agreement with previous theoretical work [8]. However, note that consecutive attosecond pulses in the train have opposite helicity, as indicated by the arrows located beneath each attosecond pulse, so that the averaged ellipticity across the entire attosecond pulse train is nearly zero, which in the frequency domain manifests itself as linearly polarized harmonics.

As illustrated in 2b, the introduction of a small p-polarized component suppresses one of the two attosecond pulses emitted each cycle. The result is an attosecond pulse train with periodic spacing between pulses and where all pulses within the train have the same helicity. Inspection of the plasma density dynamics shows that the introduction of a small p-polarized component to a purely s-polarized driving laser is effective at mostly suppressing one of the two attosecond pulses emitted each cycle. Note that for I_s/I_L = 0.99 there is still some weak emission during the suppressed half cycle, which is why lower values of I_s/I_L are required to achieve near CP low order harmonics. As I_s/I_L is decreased further to 0.5, a CP attosecond pulse train is again observed, but the helicity of the attosecond pulse train has flipped to an orientation which coincides with the reflected fundamental.

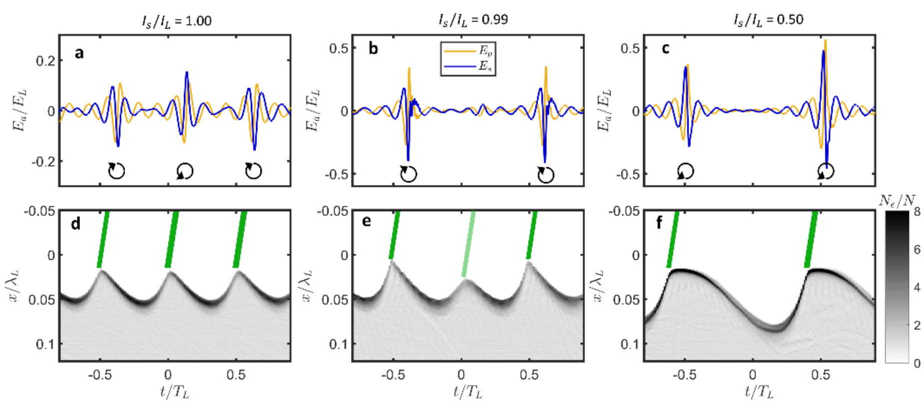

Figure 2. One-dimensional particle-in-cell simulation of the attosecond pulse train (a-c), space-time electron number density contours (d-f), and the electron current density at the front surface of the electron number density for I_s/I_L = 1.0 (a, d), 0.99 (b, e), and 0.50 (c, f). In a-c, the arrows indicate the helicity for each individual attosecond pulse. In d-f the black and orange lines mark the trajectory of attosecond pulses after emission. Simulation parameters: a_0 = 160, N = 400, θ = 45º, τ/T_L = 5, L = 0, I_s/I_L = varied, $\varphi_{sp} = \pi/2$, $\lambda_L/\Delta x$ = 1000, and particles/cell = 100.

4. Conclusion

In summary, we showed that tuning the ellipticity of the driving laser in relativistic laser-solid interactions leads to the emission of co-rotating and counter-rotating circularly polarized harmonics, depending on whether the driving laser is nearly circularly polarized or nearly S-polarized, respectively.

5. Acknowledgements and References

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