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Plasma Photonics for Generation of Exawatt to Zettawatt Laser Pulses

Min Sup Hur
[1] Department of physics, UNIST
e-mail (speaker): mshur@unist.ac.kr

1. Introduction

Chirped-pulse amplification (CPA) is nearing its technological limits, with peak powers capped at a few petawatts. Scaling toward exawatt and zettawatt regimes requires alternative compression methods. Exawatt pulses would enable experimental access to pair production, while zettawatt pulses could probe the Schwinger limit and even Hawking radiation in the lab. The main limitation of CPA lies in the damage susceptibility of solid-state compression gratings at high fluence. Therefore, compact, damage-free compression techniques are essential for progress.

Plasma-based pulse compression offers a promising path forward. Being already ionized, plasma is immune to further laser-induced damage and is highly dispersive—allowing it to act as an efficient compression medium. Approaches such as Raman backward amplification (RBA) [1] and Brillouin scattering [2] use dynamic plasma gratings, while more recent studies have explored static plasma gratings, achieving compression factors of 10–100 through reflective [3] and transmissive [4] configurations.

We recently introduced a novel scheme using a smooth, high-density plasma mirror with a density gradient to compress a negatively chirped pulse. Frequency-dependent reflection leads to high compression ratios, as shown in our PIC simulations published in *Nature Photonics* [5]. However, two main challenges remain: (1) producing large, near-critical density plasma mirrors is difficult, and (2) even small density fluctuations can severely degrade compression.

To address this, we propose gradient plasma photonic crystal (GPPC). This hybrid approach allows for lower mirror densities and reduced sensitivity to fluctuations. We present analytical results and PIC simulations demonstrating its effectiveness.

2. Theoretical Analysis of Plasma Gratings

The band structure of plasma gratings depends on three parameters: the base density n_a , modulation depth δn, and grating period Λ, as shown in Fig. 1(a). Using the dispersion relation from Ref. [6], we analyzed how these parameters affect the upper cutoff frequency W_2 of the first bandgap (Fig. 1a). Figure 1 (a) shows that using W_2 for reflection allows n_a to be reduced to one-third of the value required in the original scheme. Figure 1 (b) and (c) shows that W_2 is sensitively increasing for increasing n_a implying that the GPPC structure can be a good candidate for a chirped mirror that can be used for pulse compression. Figure 1 (c) shows that W_2 changes even more steeply, but in opposite direction, for increasing Λ. Since Λ is small (large) in the dip (bump) of density fluctuation, combination of n_a and Λ can enable local compensation of density fluctuation effects. Figure 1 (d) is the PIC simulation of pulse compression in the presence of density fluctuation. This compensation mechanism, along with the reduced density requirement, makes the GPPC approach more plausable for robust and practical compressor.

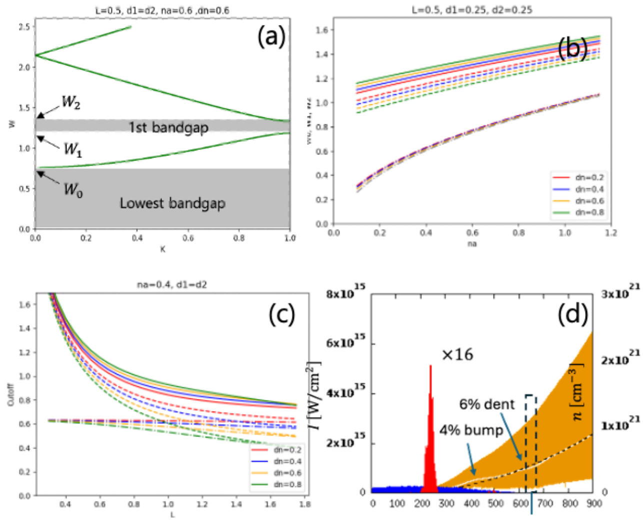

Fig. 1. (a) Band structure of plasma photonic crystal. (b,c) Change of W_2 (cutoff freq.) for increasing n_a and Λ, respectively. (d) PIC simulation of pulse compression by a fluctuated GPPC.

3. Summary

We propose GPPC structure to significantly reduce the required plasma density, easing experimental constraints, and make the compression robust to density fluctuations. Simulation results imply that the idea works well.

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