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High-Order Harmonic Generation in Gas Jet Targets in the Relativistic Laser-Plasma Interaction Regime
ガスジェットターゲット中での相対論的レーザープラズマ相互作用による高次高調波の生成

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We experimentally demonstrate a new regime of high-order harmonic generation by relativistic-irradiance lasers in gas jet targets. Bright harmonics with both the odd and even orders are generated in the forward direction by either linearly or circularly polarized pulses, while the base harmonic frequency is downshifted. With a 9 TW laser, the harmonics reach the 'water window' spectral region. Using a 120 TW laser, we demonstrate the photon number scalability up to ~40 μJ/sr per harmonic at 120 eV. We introduce a new harmonic generation mechanism based on the relativistic plasma phenomena and catastrophe theory.

1. Introduction

Up to now, several high-order harmonic generation mechanisms have been demonstrated, including atomic harmonics, relativistic harmonics from solid targets, nonlinear Thomson scattering, etc. We demonstrate a new harmonic generation mechanism by relativistic-irradiance lasers in gas jet targets [1].

2. Experimental Setup

We have performed experimental campaigns using two lasers, the J-KAREN [2] (KPSI JAEA, 9 TW, 27 fs, 4×10^{18} W/cm^2) and Astra Gemini [3] (CLF RAL, 170 TW, 54 fs, 5×10^{18} W/cm^2). Focusing laser pulses onto supersonic He gas jets [1 mm and 0.5 mm diameters, (2-8)$\times10^{19}$ cm^{-3}], we have recorded harmonics in the laser propagation

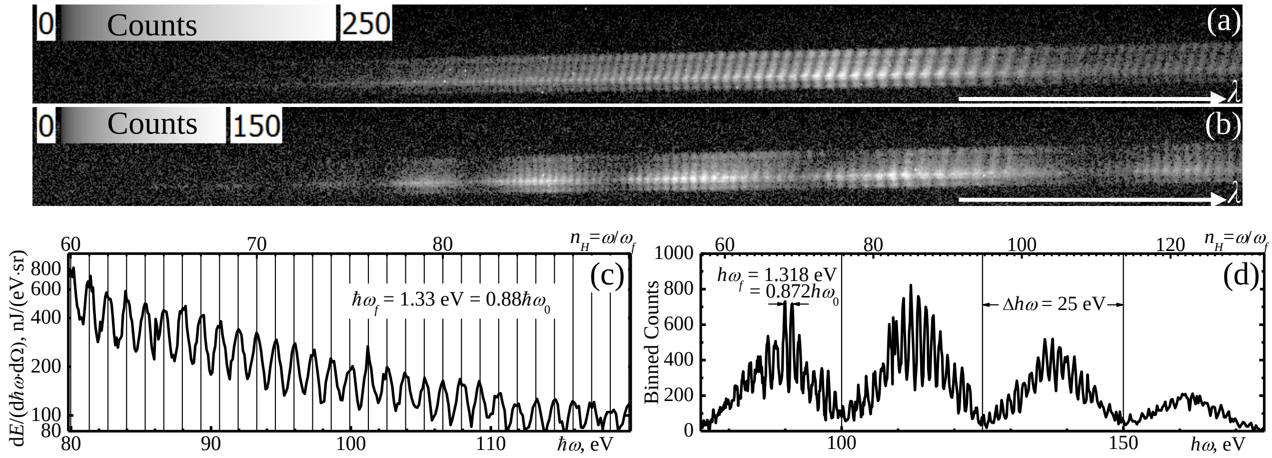

Fig. 1. Typical harmonic spectra obtained with the J-KAREN laser at 9 TW. The base harmonic frequency ω_f is downshifted from the laser frequency ω_0. Laser wavelength λ_0=820 nm, $\hbar\omega_0$=1.51 eV. (a), (b): raw CCD data of a typical comb-like (a) and modulated (b) spectra. (c), (d): lineouts of the spectra shown in (a) and (b), respectively.

direction employing flat-field grazing-incidence spectrographs (gold-coated grazing-incidence collecting mirror, optical blocking filters, spherical varied-linespace grating, and back-illuminated CCD). The wavelength calibration is carefully performed using spectra of Ar and Ne plasmas excited in-place by the same lasers. The harmonics' energy and photon numbers are conservatively estimated using idealized spectrograph throughputs. All spectra are obtained in the single shot mode.

3. Results

Bright odd and even order harmonics are emitted in the forward direction, with the downshifted base harmonic frequency. The harmonics are generated by either linearly or circularly polarized pulses.

Figure 1 shows typical spectra. With the 9 TW laser, the harmonics extend to the spectrograph throughput cutoff at 360 eV, within the 'water window' spectral region. The harmonics' energy within the 'water window' is 0.8±0.1 µJ/sr. With the 120 TW laser producing ~40 µJ/sr per harmonic at 120 eV, we demonstrated the harmonic generation process scalability in terms of photon number. The highest resolved harmonic order is ~370 with the base frequency corresponding to 0.43 eV.

4. New Harmonic Generation Mechanism

Known mechanisms (atomic harmonics, betatron radiation, nonlinear Thomson scattering) cannot explain the observed harmonics. Using high-resolution 2D and 3D Particle in Cell simulations, we introduce a new mechanism of harmonic generation by relativistic-irradiance lasers in underdense plasmas [1]. It is based on the phenomena inherent in the relativistic laser plasma: self-focusing [4], [5], cavity evacuation [5], [6], and bow wave generation [7], and collective radiation of a compact electric charge driven by a laser field [8]. The formation of the compact charge in the form of a density spike is explained with catastrophe theory [9]. Two 'fold'-type singularities in the electron density are formed due to the cavity and bow wave generation. At the joining of these two singularities, a higher-order 'cusp' singularity, or electron density spike, is formed. Its nonlinear oscillations lead to the collective radiation of high-order harmonics.

5. Conclusion

Using femtosecond lasers and replenishable, debris-free gas jet targets, we demonstrate a novel harmonic generation regime, which can be immediately applied in ultrafast science, medicine and technology requiring compact coherent X-ray sources. Scalings are favorable for diffractive imaging of nanostructures, viruses, or cells.

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