Quasi-phase-matching control of high-harmonic generation with Preformed plasma structures

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Motivation:

- State of art HHG as a promising tabletop XUV source
- Technique to produce plasma dots as a new QPM modulation structure
- The optical properties of plasma dots with the SDE analytical model
- The quasi-phase matching control of HHG
The development of HHG

- Highly directional
- Sharing temporal and spatial coherence properties with driving laser

- High repetition rate with femto seconds duration

- Tunable table-top light source from UV to Soft X-ray (~1keV)

- The cutoff is not limited by theory

But

- Extremely low efficiency 10e-10~10e-5 for each order of harmonics mainly due to laser dispersion because of the highly ionization of neutral gas and phase mismatch between fundamental driving laser and high harmonics
The development of HHG

Ionization induced driven laser pulse refraction

+ 

Phase mismatch between fundamental driving laser and high harmonics

Structured hallow ablative waveguide

Capillary Discharge

Multiple color drive

Counter-propagating quasi-cw field

Tailoring the wavefront of the driven pulser

Mixed gases

![Graph showing normalized intensity vs wavelength](image)

* Zepf M et al., PRL. 5;99(14):143901. (2007)

The periodic plasma structure

Fig 1.1 interferogram of sample plasma channel (Hydraden 100mbar)

Fig 1.2 interferogram of sample plasma dots (Ar 80mbar)

Fig 1.3 interferogram of sample plasma dots (Ar 100mbar)
Plasma channel guiding experiment setup:

Experiment setup

1053nm 10Hz
300fs 20mJ

Keep align system

delay line

delay line

optical spectrometer

vacuum chamber

XUV spectrometer

ccd
Vacuum
dielectric plates
drilling 300 micron thickness 250 micron

pulser+
~ 30 kV
current rising time
< 20 ns

thyratron

spark gap

For 100mbar Ar, the ionization rate:
- max: 65%
- average: 40%
Refractive index profile of plasma dots

\[ n_p = \sqrt{1 - \frac{4\pi en_e}{2\omega_l m_e}} \]
Optical properties of plasma dots with the SDE analytical model

\[
\frac{\partial^2 R}{\partial Z^2} - R^{-3} - \frac{2R^{-1}}{\eta_0^2 r_0^2} \int_0^\infty dX \left( \frac{\partial^2 \eta^2}{\partial X^2} \right) X \cdot e^{-X} = 0
\]

\[\eta = \eta_0 + \Delta \eta,\]

\[\eta_0 \equiv 1 (\text{linear index contribution from the bound atomic electrons})\]

\[\Delta \eta = \Delta \eta_p + \Delta \eta_r + \Delta \eta_a + \Delta \eta_c + \Delta \eta_\perp\]

\[\Delta \eta_p = -\omega_0^2 / 2\omega_0^2 (\text{linear contribution from free plasma electrons})\]

\[*\Delta \eta_r = -\Delta \eta_p a_0^2 / 4 (\text{relative contribution from free plasma electrons})\]

\[*\Delta \eta_a = \eta_2 I (\text{nonlinear contribution from atomic electrons})\]

\[*\Delta \eta_c = (\Delta n_c / n_p) r^2 / r_0^2 (\text{contribution from a preformed plasma channel})\]

\[\Delta \eta_\perp = -2c^2 / (\omega_0 r_0)^2 (\text{contribution from finite laser spot size})\]
\[
\frac{\partial^2 R}{\partial Z^2} - R^{-3}(1 - \frac{\Delta n_c}{n_p} - \frac{P}{P_r} - \frac{P}{P_a}) = 0
\]

\[
P_a = \frac{\lambda_0^2}{(2\pi \eta_0 \eta_2)}
\]

\[
P_r = 2c (q/r_e)^2 (\omega_0 / \omega_p)^2
\]

\[
P = (\pi/2) \eta_0 I r_s^2
\]

\[
P_{\text{crit}} = \frac{(1 - \Delta n_c / n_c) P_r P_a}{(P_r + P_a)}
\]

If \( P / P_r \leq 1, r_0 / \lambda > P[TW]/0.0216\)^{0.5}, \( \Delta Z << \lambda_p r_{c1} / 2\lambda \)

\[
r_s^2 = r_0^{-2} - r_0^{-2} \left( \frac{\lambda_p r_{c1}}{\pi r_0^2} \right)^2 \left[ \frac{P}{P_r} - \left( \frac{P}{3\pi P_r r_{c1}} \right)^2 - 1 \right] + \left[ 1 + \left( \frac{\lambda_p r_{c1}}{\pi r_0^2} \right)^2 \left[ \frac{P}{P_r} - \left( \frac{P}{3\pi P_r r_{c1}} \right)^2 - 1 \right] \right] \cos \left[ \frac{2\lambda (z - z_0)}{\lambda_p r_{c1}} \right]
\]


Focal spot size:
\[ r_f = r_0 \left( \frac{1 - g\Delta Z^2}{1 + g^2 Z^2 R_0 \Delta Z^2} \right)^{0.5} \]

Focal distance:
\[ z_f = \Delta Z \left[ 1 + \frac{g Z^2 R_0 (1 - g) \Delta Z^2}{1 + g^2 Z^2 R_0 \Delta Z^2} \right] \]
& High repetition rate (up to 10 Hz)
& tunable periodic plasma micro-structures
& fast rise time compatible with delay line of high power lasers
& flexible to setup compound micro-lens systems for multipurpose application
& sharing similar optical property as conventional lens but high power compatible and optical probe beam accessible
& flexible plasma lens systems for high power laser

<table>
<thead>
<tr>
<th>Longitudinal Length (mm)</th>
<th>$r_e$ (mm)*</th>
<th>Neutral gas (Ar) pressure (mbar)</th>
<th>(Ar) neutral gas density ($10^{18}$/cm$^3$)</th>
<th>$n_0$ (/cm$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25-1.0</td>
<td>0.25-0.50</td>
<td>80-150</td>
<td>1.90-3.80</td>
<td>$10^{17}-10^{19}$</td>
</tr>
</tbody>
</table>

Tab 1.1 Plasma dots structure parameters

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Intensity (w/cm$^2$)</th>
<th>Spot size at the entrance of the bubble structure (micron)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1053</td>
<td>$10^{15}$</td>
<td>50-100</td>
</tr>
</tbody>
</table>

Tab 1.2 Sample laser parameters

The focusing properties of one single dot structure

<table>
<thead>
<tr>
<th>Focal length (micron)</th>
<th>Focal spot size (micron)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50-15000</td>
<td>18-25</td>
</tr>
</tbody>
</table>
Mechanism of QPM

Phase mismatch

\[ \Delta k = n k_n - k_0 = \Delta k_{\text{waveguide}} + \Delta k_{\text{plasma}} + \Delta k_{\text{neutrals}} \]

No PM

\[ \eta > \eta_c (\text{Ar} \leq 5\%, \text{Ne} \leq 1\%, \text{He} \leq 0.5\%), \text{then no} \ \Delta k = 0 \]

E field of harmonics*

\[ E_n \propto \int_{0}^{L} E_0^N d(z) e^{-i\Delta k z} \, dz \]

Modulation depth

\[ d(z) = d_{\text{eff}} \sum_{m=\infty}^{\infty} G_m e^{iK_m z} \quad (K_m = 2\pi m / \Delta) \]

QPM item

\[ E_n \propto \int_{0}^{L} E_0^N d_{\text{eff}} \sum_{m=-\infty}^{\infty} G_m e^{-i(\Delta k - K_m) z} \, dz \]

Enhancement of HHG with Plasma dots

ADK ionization process during a laser pulse

\[ E_{\omega}^q (L) \propto E_{\omega}^{q \text{ eff}} L |G(\Delta k)|, \]

Enhancement factor with preformed plasma dots in the sample (\(d_{\text{eff}}=0.1\), modulation number \(N=20\), modulation length \(\Delta L=250\) micron)

Optimization

\[ G[\Delta k(\lambda)] = \frac{1}{N \cdot \Delta L} \left| \sum_{p=0}^{N-1} g(z_p) \int_{z_p}^{z_p+\Delta L} e^{-i\Delta k(\lambda) \xi} d\xi \right|, \]
Summary

What is shown here is a new method of producing a QPM structure-plasma dots which is characterized with a high repetition rate, repeatability & tunablity.

Although a very simple model is used to analyze the QPM conditions, it is reasonable to foresee the potential of utilizing plasma dots in combination with a discharge plasma waveguide and QPM techniques to generate much short wavelengths more efficiently.