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

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Introduction:

In HHG process, the nonlinear interaction between an intense laser and a material, typically a gas, produces high-order harmonics of the fundamental laser. The whole process can be interpreted by a 3-step semi-classical model: firstly, the laser field ionizes the atom or molecule, it then accelerates the liberated electron away from the ion, and finally, high-order harmonic photons generated when the laser field reverses and the oscillating electron recollides with the parent ion. The highest photon energy that can be produced via this interaction is predicted by the cutoff rule [1]: $h\nu_{max}= I_p+3.17U_p$, where I_p is the ionization potential of the atom and U_p is the pondermotive energy of the electron in the laser field, which is proportional to λI_L. Here I_L is the peak laser intensity and λ is the wavelength of the driving laser field. From the cutoff rule, the range of photon energies that are generated in HHG is determined by the laser intensity. However, according to most experiments, the maximum observed HHG photon energy has been limited not by the available laser intensity, but by the saturation intensity I_s at which over 98% of target atoms are ionized. This is because at near full ionization in a medium, the ionization induced refraction of the laser beam seriously reduces the effective laser intensity. Meanwhile, the phase mismatch between different frequency components in the nonlinear medium are enhanced; thus, their coherence lengths are decreased, which further limits the number of atoms contributing to the harmonic emission. To obtain the highest possible photon energy and output photon flux, without changing the laser duration or gas species, in order, a waveguide can be used to help the propagation of the laser pulse and somewhat compensate the phase difference. In past work, quasi-phase matching (QPM) schemes have been demonstrated to overcome the phase mismatch [2-3]. Moreover, for external guiding schemes, such as HHG in capillary discharge plasma have been proved to effectively suppress energy loss in HHG, due to ionization-induced defocusing of the laser [4].

In this paper, we present a new method to generate a QPM modulation structure: a highly repeatable array of plasma dots with well controllable channel-like optical guiding properties. By exploring the property of the plasma dots via analytical model, we conclude that, it is possible to combine both advantages of QPM and multiply ionized discharge plasma waveguides to selectively enhance a certain spectral region of HHG.

Discussion:

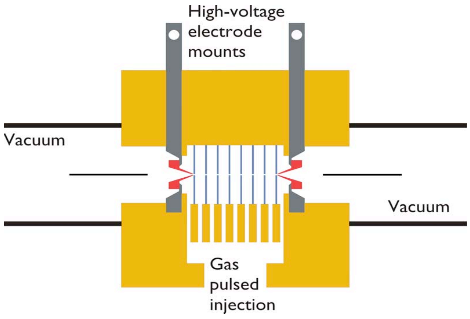

Fig.1. Schematic of structured gas cell

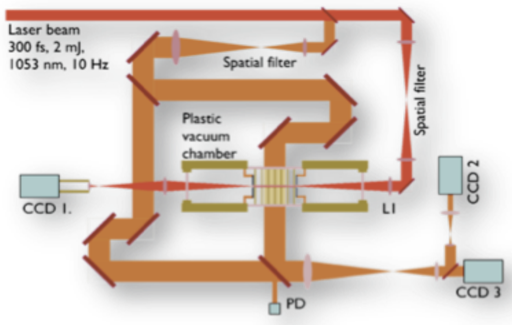

Fig.2. Schematic of the optical setup

1. Technique to produce plasma dots:

The whole design is based on a capactive discharge in a structured gas cell (Fig.1.) with a fast thyratron switch. In the gas cell, the space between the electrodes is separated by a sequence of thin dielectric plates made of alumina (thickness250 μm) with drillings (Ø 150μm) at the predefined guiding axis. High-voltage pluser (up to 100 kV at an impedance of 125 Ω) with duration 200ns, rise-time 20ns are applied to the electrodes to produce and heat plasma on the axis. When the arc discharge initiates, the rising current is forced to pass through the drillings in the dieletric plates to enhance gas ionization along the axis. In a former experiment, 2cm gas cells [5] was used to produce straight plasma channels. Comparing with 2cm device, except the difference of filling gas species, the new 8cm gas cell uses a longer separation space between dieletric plates. Thus, the electric field along aixs is weeker than preciously which makes the breakdown process slow down. As a consquence, the current density near the apertures is much higher than that in the middle of two dieletric plates and this make the heating of the plasma around apertures reinforced to generate plasma dots structure.

2. Plasma dots optical property:

In order to obtain a time-dependent density profile of plasma dots, the structured gas cell is transversely probed in a Mach-Zehnder interferometer as our former experiment [5] (fig.2). The plasma density profile is obtained by a procedure very similar to [6]: First, the phase shift in obtained by 2-dimensional FFT analysis. Following, plasma density profile is retrieved by Able inversion. Fig.3. is interferogram images of plasma dots. Fig.4.(a) and (b) shows that plasma dots share similar plasma density profile and refractive index with short

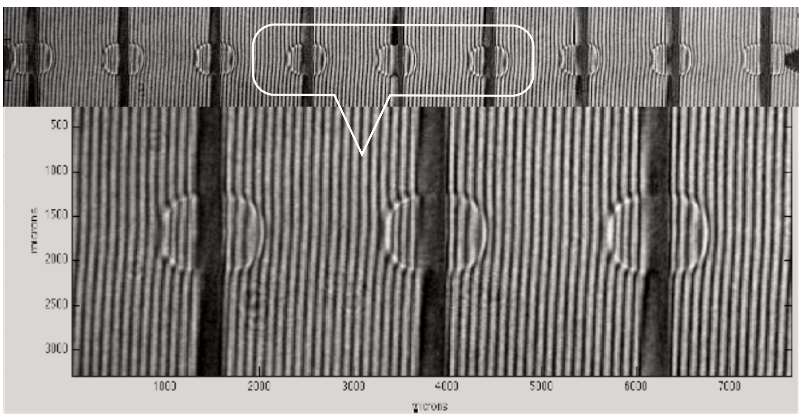

Fig.3. Interferogram images obtain of plasma dots with a delay of 50 ns after start of trigger, with backing pressure Ar 80 mbar, pluser voltage set at 16 kV

plasma lenses [7] which leads to focusing effects.

In order to obtain the focal length and focal spot size of the plasma dots, a analytical model based on the source-dependent expansion (SDE) method is employed [8]. This model can be simplified into a thin plasma lens regime, in the case of $\Delta << \Delta_c \equiv \frac{\lambda_p r_{c1}}{2\lambda}$, Δ is the thickness of plasma lens, Δ_c is the critical thickness, λ_p is the plasma wavelength, λ is the laser wavelength, r_{c1} is the nominal channel radius [8]. Then the focal distance z_f and focal spot size r_f are given by:

$$z_f = \Delta[1 + \frac{g z_{R0}^2 (1 - g\Delta Z^2)}{1 + g^2 Z^2 z_{R0}^2}] \sim (1); \qquad r_f = r_0 (\frac{1 - g\Delta Z^2}{1 + g^2 Z^2 z_{R0}^2})^{0.5} \sim (2)$$

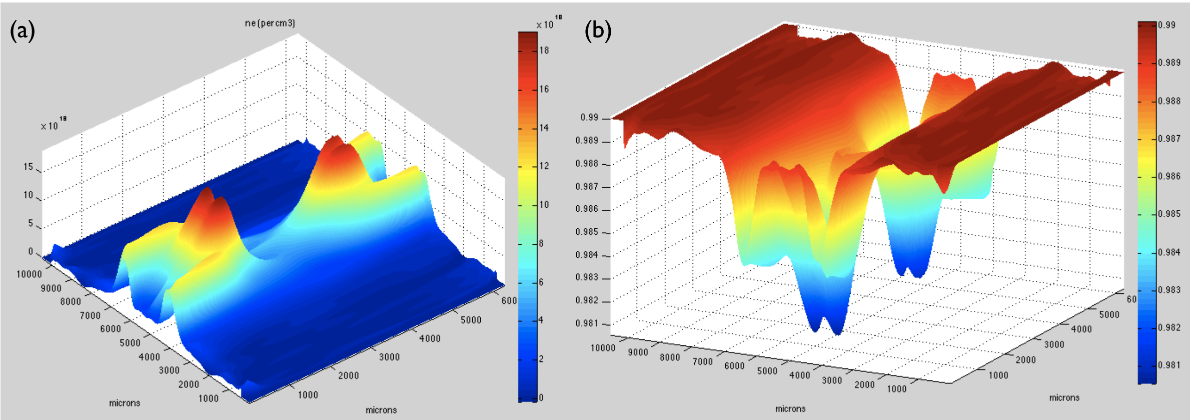

Fig. 4. (a)Plasma dots density profile(80 mbar Ar, with 16 kV at the delay of 50 ns) and(b) the corresponding real part of the plasma induced refractive index

where $z_{R0} = \pi r_0^2 / \lambda$, r_0 is the initial beam waist, and $g \approx (\frac{\lambda}{\lambda_p r_{c1}})^2 [1 - (\frac{\lambda_p r_{c1}}{\lambda z_{R0}})^2]$.

When laser pluse (30 fs, 10 mJ, 800 nm, r_0= 100 μm) is F/30 focused into one single plasma dot, we can rend the z_f is & r_f with the measured profile of plasma dots. For instance, the sample plasma dots in Fig.4. z_f is aound 250μm & r_f is less than 50μm. Through tailoring the backing gas pressure of Ar, discharge voltage and current, the relevant parameters of plasma dots in Eq.(1)&Eq.(2) can be tuned. According to the experimental data, the calculated z_f scales from 4cm to 50 microns with focal spot size r_f smaller than 80 microns.

3. QPM control of HHG

With plasma dots periodically focus the fundamental laser pulse ω_0 along the axis, the critical intensity, which will turn on the emission of a narrow region of HHG spectrum near the cutoff, is periodically met. And in this simple way, the conditions of QPM are satisfied.

We will now use typical plasma dots parameters (Fig.4.) to analyze the QPM mechanism. In order to simplify the model, it is a good approximation to treat the preformed plasma line as a straight waveguide. Using ADK theory [9], we calculate the level of ionization for a given harmonic generated by the laser pulse. We obtain the wave vector mismatch between ω_0 and

ω_q (λ, a, u_{11}, η, N_{atm}, P, δ, r_e are driven laser wavelength, waveguide radius, first zero of Bessel function J_0, ionization fraction, number density at 1 atm, gas pressure, refractive index of neutral gas for ω_0 at 1 atmosphere and classical electron radius, respectively):

$$\Delta k = k_q - qk_0 = \frac{qu_{11}^2\lambda}{4\pi a^2} + P\eta N_{atm} r_e (q\lambda - \lambda/q) - \frac{2\pi(1-\eta)Pq}{\lambda}(\delta(\lambda) - \delta(\lambda)/q), \quad (2)$$

Under the conditions of low pressure, fully ionization near the axis and high tunnel ionization rate, the contribution of the neutral gas to the phase mismatch can be neglected, and the dominant terms in Eq. (2) are due to the waveguide and plasma. Using reasonable assumption that $q\lambda >> \lambda/q$, the phase mismatch is then given by: $\Delta k = \frac{qu_{11}^2\lambda}{4\pi a^2} + \frac{qn_e e^2\lambda}{4\pi m_e \varepsilon_0 c^2}$, (3)

Where n_e is the electron density and ε_0 is the electric constant. In the simple model of HHG [2], the field of harmonic order q after propagating a distance of L in the nonlinear medium is given by: $E_{\omega}^{q}(L) \propto E_{\omega}^{q} d_{eff} L |G(\Delta k)|$, (4)

Where $G(\Delta k)$ is given by(N, $g(z_p)$, ΔL, are number of modulation, the modulation depth and modulation length): $G[\Delta k(\lambda)] = \frac{1}{N \cdot \Delta L}\left|\sum_{p=0}^{N-1} g(z_p) \int_{z_p}^{z_p+\Delta L} e^{(-i\Delta k(\lambda)\xi)} d\xi\right|$, (5)

Since the calculated harmonic intensity scales $|G[\Delta k(\lambda)]|^2$, the problem turns into how to make $G(\Delta k)$ be maximum to achieve the largest conversion efficiency for a specific order of high harmonic. Here, we have only considered a very simple model, whereas the absorption loss of the driving laser, model beating are not taken into account. The harmonics which are enhanced around 20nm, under a modulation depth of 0.1, N=20, ΔL=250μm, the enhancement factor over no modulation is more than 20.

Conclusion

We have shown that 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.

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