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Original research article

The effect of gas pressure and slit width on the high order harmonic generation in helium-filled slab waveguide

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A B S T R A C T

We measured the dependence of the intensity of high harmonics on the gas pressure in slab waveguide. The phase matching of 61st high harmonic was obtained according to the quadratic dependence of the increase in efficiency with pressure. For higher order harmonics such as H91, periodic oscillations of the harmonic intensity with gas pressure was observed. We also studied the effect of the slit width of the slab waveguide on the high harmonics generation. The influence of the slit width on laser transverse mode and phase mismatching conditions can be used to explain this effect.

1. Introduction

High-order harmonic generation (HHG) has been studied for many years since it was observed by Macpherson et al. [1]. The motivation for the development of HHG comes from many areas of science and technology. For example, it may provide a source of coherent and ultrashort radiation that can be used for pump-probe experiments in atomic and molecular spectroscopy [2–4], observation of microscopic biological structures [5], even the external seeding of free electron lasers [6]. A gas-filled capillary setup that can be used to generate high harmonics has been developed for many years because of the realization of the phase matching and qusi-phase matching between the fundamental light and the high harmonics in this geometry [7,8]. However, in order to implement the qusi-phase matching of high harmonics, a periodical structure in the capillary is produced with a method named glassblowing which is a complicated technology [8]. In recent experiments, our results showed that a slab waveguide could also be used to generate high harmonics efficiently and restrains the effect of the ionization-induced laser defocusing [9]. More important, fabrication of the periodical structures on flat surface is easier than that in capillary. However, many characteristics of the high harmonics generated in the slab waveguide is unknown. Therefore, further studies are still needed to fully understand its physical mechanism and process.

In this paper, the He-filled slab waveguide was used to generate high harmonics for wavelength between 5 and 20 nm. The spectra of high harmonics under different gas pressure was recorded. The dependence of the intensity of high harmonics on the gas pressure showed that phase matched 61st high harmonic in this geometry was obtained. On the contrary, higher order harmonics presented a periodic oscillation of the intensity with gas pressure. The influence of the slit width of the slab waveguide on the HHG in this geometry was then investigated. The results can be explained by the contributions of laser transverse mode and phase mismatching conditions in the slab waveguide to the HHG.

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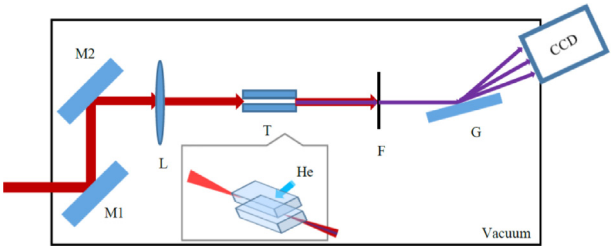

Fig. 1. Setup for HHG in a gas-filled slab waveguide shown in the inset. M1 and M2: mirrors, L: lens, T: target, F: filter, G: grating.

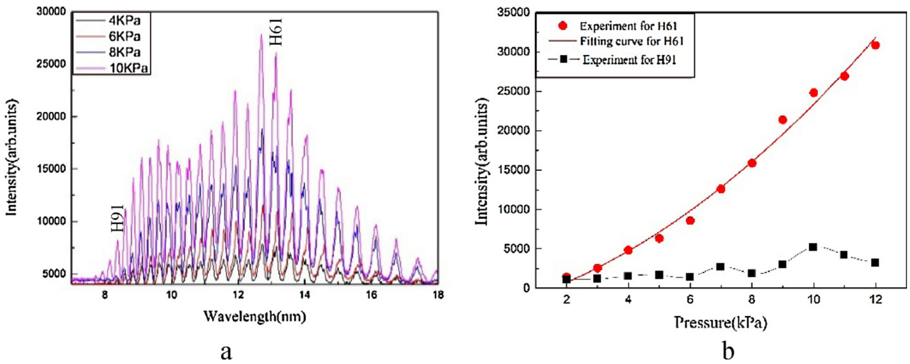

Fig. 2. (a) Spectra of high harmonics at different gas pressure. (b) Dependence of the harmonic intensity for H61 and H91 on the gas pressure.

2. Experimental setup

Our experimental setup is sketched in Fig. 1. The femtosecond laser pulses (3.5 mJ, 75 fs, 800 nm) propagated into the vacuum chamber and were focused with a f = 400 mm lens into a gas-filled slab waveguide. The laser energy that reached the slab waveguide was about 3 mJ and the beam radius at the focal spot was ~40 mm. Therefore, the calculated peak intensity at the focal spot was approximately 7.95×10^{14}W/cm^2. The lens was mounted on a motion stage in order to adjust the position of the focal spot. The slab waveguide was formed by two pieces of fused silica which were placed in parallel with a distance. This distance which can be named slit width was normally several hundred microns. The slab waveguide was 20 mm long and was backed with helium. The femtosecond laser pulses emitted from the slab waveguide were filtered by two zirconium (Zr) films. The high harmonics was detected by a XUV spectrometer (Model 251MX, McPherson) which consists of a varied line spacing concave grating (1200grooves/mm) and a XUV charge-coupled device (CCD) (PI-MTE, Princeton).

3. Results and discussion

Fig. 2(a) shows the spectra of high harmonics recorded at gas pressure of 4 kPa, 6 kPa, 8 kPa and 10 kPa. In this case, the slit width of slab waveguide was ~200 μm. Because of the limitation of the spectrometer, only radiations between 5 and 20 nm was detected. The maximum harmonic order emitted from the He-filled slab waveguide reaches H99 under our current experimental conditions. Mover, this result shows that with increasing gas pressure, the cutoff region for this geometry is apparent rather than gradually decreasing, as with the gas cell. This indicates that the gas-filled slab waveguide restrains the effect of laser defocusing because the light is guided by the walls of the waveguide [9,10]. The intensity of harmonics H61 and H91 versus gas pressure is shown in Fig. 2(b). For the 61 st harmonic, Fig. 2(b) shows a monotonic increase in harmonic intensity with gas pressure. Furthermore, the red solid line presents a fit close to a p^2 law which is in agreement with theory of phase matching [11].

However, the higher order high harmonic such as 91st harmonic shows a periodic oscillation of the intensity with gas pressure. This characteristic of the 91st harmonic should be attributed to the short coherence length which is decided by $L_c = \pi/\Delta k_q$. The phase matching relation Δk_q for the qth harmonic order can be written as [12]

$$\Delta k_q = k_q - qk_1 = \Delta k_{q,geo} + \Delta k_{q,el} + \Delta k_{q,at} \tag{1}$$

in which $\Delta k_{q,geo}$, $\Delta k_{q,el}$ and $\Delta k_{q,at}$ are geometric wave vector mismatch, electronic wave vector mismatch and atom wave vector mismatch respectively. In our experiment, the laser pulse with the peak intensity of 7.95×10^{14}W/cm^2 results in a