High-order harmonics in static gas target by 795-nm Ti:sapphire femtosecond laser pulses

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The 5th−23rd high-order harmonics generation in rare gases in static gas target with 120-fs, 85-mJ/pulse, 10-Hz laser system was investigated. Compared with the traditional gas target, static gas target is simple to be used in experiment, and the experimental parameters can be easily controlled. The effects on high-order harmonics due to laser intensities (energy), polarization, gas densities, confocal parameter, and phase mismatch were studied in this paper.

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The nonlinear process of high-order harmonic generation (HHG) can provide tunable, coherent, ultra-short, extreme ultraviolet (XUV) radiation. After Mcpherson observed high-order harmonics in Ne by using 1-ps KrF laser in 1987[1], over 100th -harmonic radiation (less than 10 nm) was got in various gases[2−4]. Besides the new coherent soft X-ray source, attosecond laser pulse output can be realized through high-order harmonic trains[5]. Up to now, Chang *et al.* observed up to 297th harmonics in helium by using an 800-nm, 26-fs, titanium-doped sapphire laser, and the generated wavelength of 2.73 nm came into "water windows"[4]. According to the semiclassical theory, the maximum photon energy of high-order harmonics can be expressed as[6] $E_{\max} = I_{\mathrm{p}} + 3.17\ U_{\mathrm{p}}$, where $U_{\mathrm{p}}(\mathrm{eV}) = 9.33 \times 10^{-14}(1+\alpha^2)[I(\mathrm{W/cm^2})][\lambda^2(\mu\mathrm{m}^2)]$ is the ponderomotive energy of the electron in a strong laser field, and I_{p} is the ionization potential of the atom. The above formula shows that long wavelength lasers and high potential atoms (molecules) help extend the maximum photon energy of the high-order harmonics.

In this paper, we study HHG processes in argon, krypton, and xenon by using a 120-fs/800-nm Ti:sapphire laser. The observed maximum order was 21, which was limited by the central wavelength (70 nm) of detectors and monochromator.

Chirped pulse amplification (CPA) technique is employed in the commercial laser system (Spectra-Physic, USA) used in the experiment. The 10-Hz Ti:sapphire laser system is operated at 795 nm and its pulse energy and width are 85 mJ and 120 fs, respectively.

The experimental setup is schematized in Fig. 1. The focused laser beam bores an incidence pinhole and an out pinhole on the two lattens, which are 3 mm away from each other in the target. The high-order harmonics from the target room are directed by XUV spectrometer and received by an R595 electron multiplier tube detector whose central wavelength is about 70 nm. Finally the time integral spectrum of HHG is measured by the 4400 signal analysis and process system.

Figure 2 shows typical time-integrated high-order harmonic spectrum in krypton and xenon at an intensity of above 10^{15} W/cm^2. In Fig. 2(a), 21st harmonic can be observed, but only 15th harmonic can be got under the same conditions except for laser polarization. Comparison between Figs. 2(a) and (b) shows that circularly polarized laser can restrain the generation of higher harmonics and has little effect on lower harmonics. The low-order harmonics generated by perturbation are not sensitive to polarization, and circular or elliptical polarization can control the generation of high-order harmonics. In Fig. 2(a) high-order harmonic (up to the 21st) in krypton can be clearly seen, the 23rd harmonic is not very obvious. In Fig. 2(d) only the 15th harmonic can be clearly seen in xenon, the 17th harmonic is not very obvious. The harmonic spectra in Figs. 2(a) and (d) were got by almost the same laser energy (35 and 37.5 mJ). In Fig. 2(c) the 17th harmonic disappears, because the incident laser intensities exceed the saturation intensity, a lot of Xe atoms were ionized. The so many generated electrons made effective laser intensity decrease, media refractive index change, which added the phase mismatch between fundamental wave and harmonics, so the conversion efficiencies decreased. The saturation of laser intensity led to disappearing of harmonics higher than 15th in Xe.

By using two lenses with different focuses, the high-order harmonic spectra in Kr are compared in Fig. 3. Although the absolute values of high-order harmonic signals in Figs. 3(a) and (b) could not be compared, from the signal-to-noise ratio we can conclude that if the confocal parameters are large, the efficiencies are high

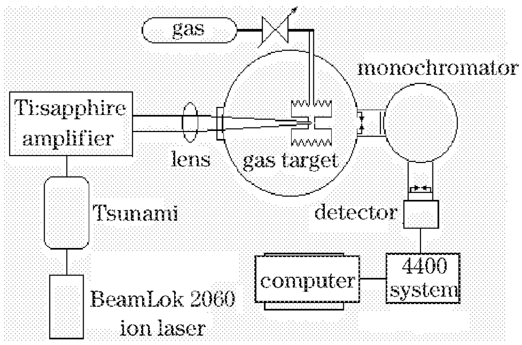

Fig. 1. Schematic of the experimental setup.

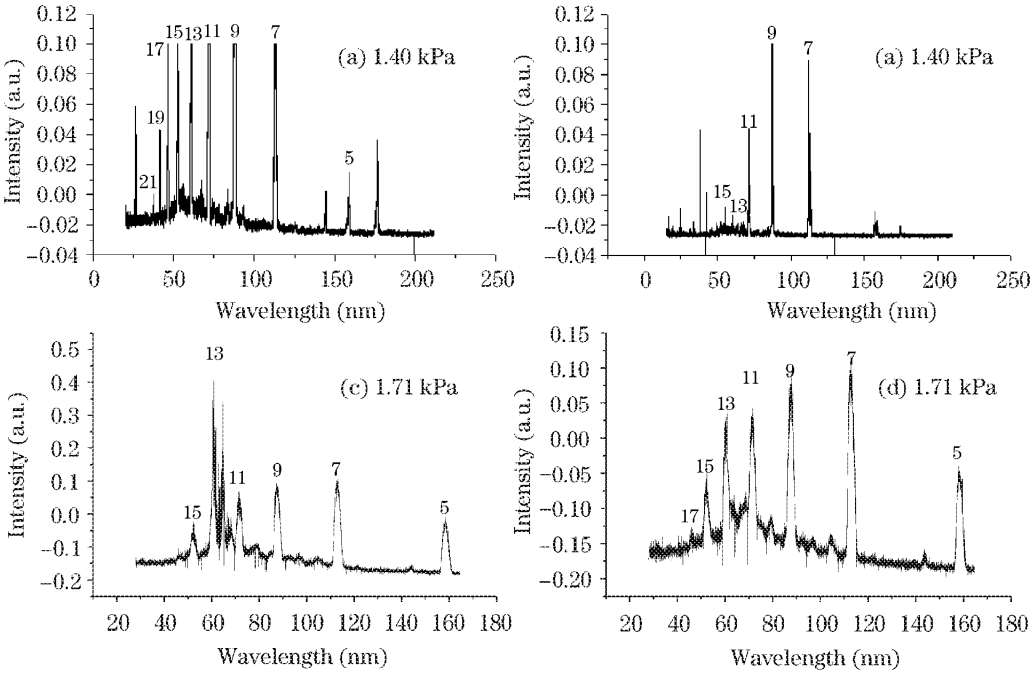

Fig. 2. Time-integrated high-order harmonic spectra (a) in Kr with a linearly-polarized laser energy of 35 mJ, (b) in Kr with a circularly-polarized laser energy of 35 mJ, (c) in Xe with a linearly-polarized laser energy of 45 mJ, and (d) in Xe with a linearly-polarized laser energy of 37.5 mJ.

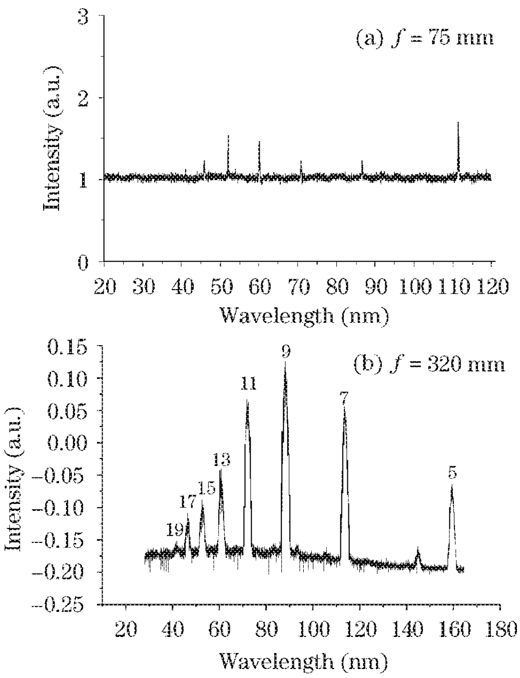

Fig. 3. The confocal parameters dependence of the high-order harmonic intensities in Kr.

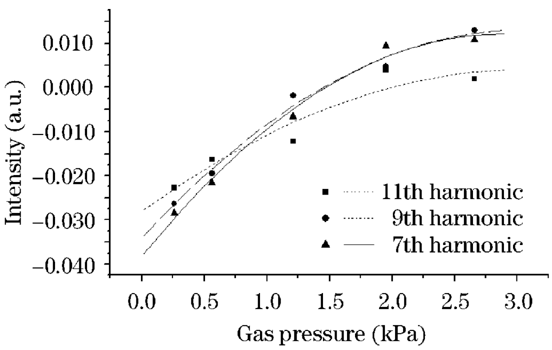

Fig. 4. The high-order harmonic intensities in Ar versus gas pressures, the laser energy is 42 mJ.

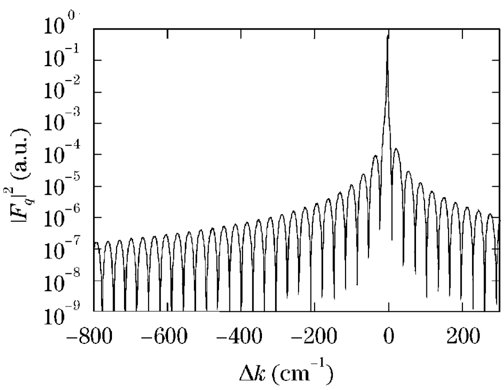

Fig. 5. Phase matching factor $|E_q|^2$ as a function of the phase mismatch Δk.

with the same conditions, namely "the weak focus favors the high-order harmonic generation".

The high-order intensities in Ar grow with gas pressures, as shown in Fig. 4. But the amplification of high-order harmonic signals is not linear because that with gas density multiplication, dispersion will increase and the free electrons resulting from ionization will multiply, which can add the phase mismatch when the high-order harmonic propagates in the media. So there should be an optimal gas density in the gas target. We did not get the optimal gas density because the detector could not bear gas pressures lower than 1.33×10^{-2} Pa.

Under the condition of the weak focus of $b \gg L$, the relationship between phase matching factor $|F_q|^2$ and phase mismatch Δk is simplified as $\sin c^{2[7]}$: $|F_q| = (2L/b)\left[\frac{\sin\{[\Delta k+2(q-1)/b]L/2\}}{[\Delta k+2(q-1)/b]L/2}\right]$. Figure 5 shows $|F_q|^2$ for the 29th harmonic and confocal parameters $b = 4$ mm ($L = 0.2$ mm). Usually it is difficult to fulfill complete phase match, and that's why the conversion efficiency of HHG is low.

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References

1. A. McPherson, G. Gibson, H. Jara, U. Johann, T. S. Luk, I. A. McIntyre, K. Boyer, and C. K. Rhodes, J. Opt. Soc. Am. B **4,** 595 (1987).
2. J. Zhou, J. Peatross, M. M. Murnane, and H. C. Kapteyn, Phys. Rev. Lett. **76,** 752 (1996).
3. J. J. Macklin, J. D. Kmetec, and C. L. Gordon III, Phys. Rev. Lett. **70,** 766 (1993).
4. Z. H. Chang, A. Rundquist, H. Wang, M. M. Murnane, and H. C. Kapteyn, Phys. Rev. Lett. **79,** 2970 (1997).
5. P. Antoine, A. L'Huillier, and M. Lewenstein, Phys. Rev. Lett. **77,** 1234 (1996).
6. J. L. Krause, K. J. Schafer, and K. C. Kulander, Phys. Rev. Lett. **68,** 3535 (1992).
7. M. Protopapas, C. H. Keitel, and P. L. Knight, Rep. Prog. Phys. **60,** 389 (1997).