Influence of circular aperture on high-order harmonic generation

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The influence of circular aperture on the intensity of high-order harmonic generation (HHG) with intense femtosecond laser pulse was studied both experimentally and theoretically. The intensity variety of HHG with the diameter of circular aperture was observed in pulsed Ar gas. The result was discussed and interpreted in terms of the theory of Hankel transform. It is found that using the Gaussian beam truncated by an aperture could enhance the conversion efficiency of HHG at certain conditions.

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The interactions of ultrashort high laser fields with matters have been studied extensively[1] with the development of laser technology[2]. The electric field of the applied laser radiation becomes comparable with or in excess of the typical atomic Coulomb field strength of $10^8 - 10^9$ V/cm, where the physical process is beyond the scope of conventional perturbation theory. There has been much interest in the process of high-order harmonic generation (HHG) in rare-gas atoms by intense laser fields[3−6] for the potential applications of high-brightness, short-pulse coherent radiation sources in the vacuum ultraviolet (VUV), extreme ultraviolet (XUV) and soft-X-ray ranges.

To date, the dependences of the spatial and temporal characteristics of the harmonic radiation on laser polarization, intensity, wavelength and pulse width have been studied experimentally and theoretically[7−12]. For example, L'Huillier *et al.* studied systematically the interplay between the single-atom response to the external laser field and macroscopic phase-matching effects, and theorized the process of HHG[13−16]. Recently, a coherent X-ray source with a wavelength as short as 2.73 nm, which reached the water window region, has been obtained in helium[17]. Meanwhile, many effects are being made to improve the conversion efficiency of HHG[18−20]. The properties of harmonic generated by a modified Gaussian laser beam have also been investigated. Toma *et al.*[21] obtained a homogeneous distribution of intensities at the focus using a circular aperture and a pair of amplifier-compressor mirrors. They found that the 13th harmonic was strongly enhanced, which exceeds the magnitude of the 11th harmonic. This behavior is a consequence of a resonant atomic process. Altucci *et al.*[22] generated Bessel-Gauss beams by using of annular aperture and then focusing of the ring-type-produced radiation. The conversion efficiencies of the third and fifth harmonic generation were found higher than those of Gaussian beams. In addition, they compared the effects of phase matching in the two different geometries. Wang *et al.*[23] increased the confocal parameter by reducing the diameter of the pumping laser beam using circular apertures. They found that the weak focusing geometry is more favorable for higher conversion efficiency than the tight one.

In this letter, we report the study on the intensities of HHG by changing the diameter of a circular aperture. At certain position of the focus in the gas jet, we found that the conversion efficiencies of high-order harmonics generated by the truncated Gaussian beams are higher than those of pure Gaussian beams. We interpreted the experimental results with the theory of Hankel transform.

The schematic of experimental setup is shown in Fig. 1. The pump laser (TSA-10, Spectra-Physics Inc., USA) is a titanium-sapphire femtosecond laser system with a regenerative chirp-pulse-amplifier (CPA) delivering 120-fs pulses with wavelength centered at 800 nm and a 10-Hz repetition rate. The maximum energy is 6 mJ. A circular aperture is placed in the Gaussian laser beam. Then the truncated Gaussian beam is focused by a lens with 70-mm focal length into a vacuum chamber containing a pulsed argon gas jet (background pressure 1 − 2 bars)[24]. The length of the gas medium in the interaction region is estimated to be about 1 mm. The generated harmonic is dispersed by a 20-cm monochromator (VM502, Acton, USA) equipped with an iridium-coated 1200-groove/mm grating and detected by a photomultiplier tube (PMT, R1459) or a windowless

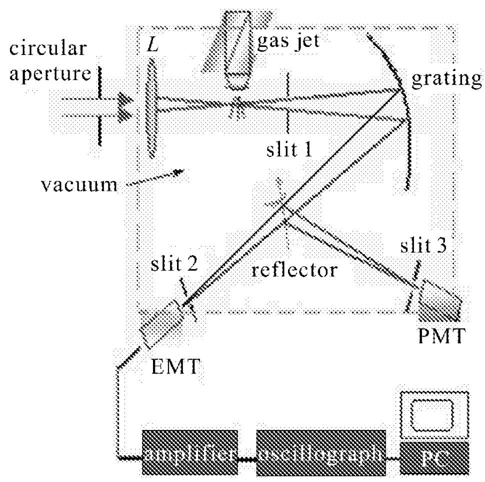

Fig. 1. The experimental setup.

electron multiplier (EMT, R595, Hamamatsu, Japan)[25]. The harmonic signal is amplified by a current amplifier, and then recorded by a digital oscilloscope connected to a personal computer.

To simulate the intensity of the laser field near the focus, we assume that the amplitude of the electrical field of the Gaussian beam can be expressed as

$$E_{\mathrm{in}}(r) = E_0 \exp\left(-\frac{r^2}{w^2}\right), \tag{1}$$

where w represents the waist of the Gaussian beam, r represents the radial coordinate, and E_0 represents the on-axis field amplitude. The field $E_{\mathrm{in}}(r)$ is let through a circular aperture and then focused by a lens of focal length f. With a Hankel transform[26], which gives the diffracted field, we can express the field, $E_{\mathrm{out}}(r,z)$, at distance z from the lens as

$$E_{\mathrm{out}}(r) = \frac{2\pi i}{z\lambda}\int_0^{\infty} r_0 E_0(r_0) J_0\left(\frac{2\pi r r_0}{z\lambda}\right) \times \exp\left[-\frac{i\pi}{z\lambda}(r^2+r_0^2)\right]\mathrm{d}r_0, \tag{2}$$

where $J_0(x)$ is the zero-order ordinary Bessel function.

We can then derive the relation between the intensity of the truncated Gaussian laser beam and that of HHG.

Figure 2 shows the normalized intensities of 11th, 13th, 15th order harmonics for different diameters of the circular aperture. Each plot is averaged over 100 shots. As can be seen, the intensity of the high-order harmonic initially keeps increasing with the diameter of the aperture until the diameter reaches 8.5 mm. Then the intensity decreases rapidly. It reaches to a stable value after several oscillations.

The amplitude of the qth order harmonic of the laser, ω, is assumed to follow $I_q(z) \propto I_1^p$, where I_1 is the laser intensity and p is a constant value[27]. Performing nonlinear fit to relative I_1 and I_q, we can get the value of p. In our experimental conditions, it is about 2.3 for 15th order harmonic, as shown in Fig. 3.

In Fig. 4, we present the variation of the intensity profile of the truncated Gaussian beam with the radius of the circular aperture, as results from numerical calculations done in the near-field region using a Hankel transform. The waist of the Gaussian beam at the aperture is about 7 mm. The intensity of the center point along the propagation axis (i.e., $r = 0$) changes wavelike with the radius of the aperture. The intensity will not change until the diffraction is slight enough, i.e., the dimension of the aperture is much larger than the FWHM of the beam. For a certain radius of the aperture, the intensities of the truncated Gaussian beam along the radial coordinate also change wavelike owing to the effect of diffraction. The macroscopic representations of these phenomena are bright-dark interlaced fringes. It should be stressed that at the focus, the intensity profile of the truncated Gaussian beam only increases with the diameter of the aperture, and does not change wavelike.

In terms of the intensity profile as shown in Fig. 4, we can calculate the intensity of the truncated Gaussian beam (I_1) by using the discretized space coordinate, in the vertical plane of the transmission direction of the laser beam. Because $I_q \propto I_1^p$ and $p = 2.3$, we perform numerical simulation for intensity of HHG versus the diameter of the aperture. The results are plotted in Fig. 5. The simulation reproduces the experimental results quite

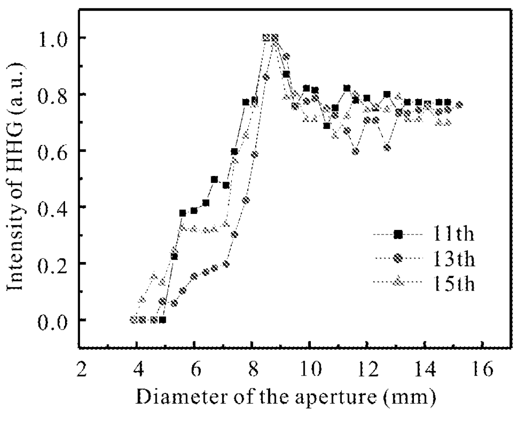

Fig. 2. The normalized intensities of 11th, 13th, 15th order harmonics versus the diameter of the circular aperture. The intensity of HHG reaches its maximum when the diameter of the aperture is 8.5 mm.

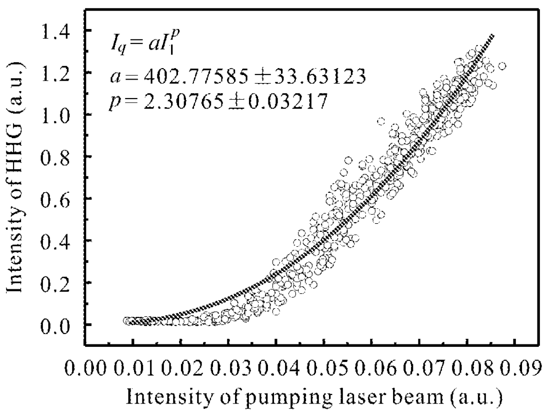

Fig. 3. I_q versus I_1 for 15th order harmonic.

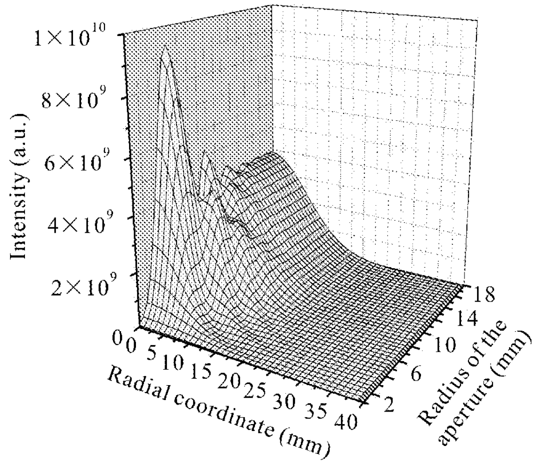

Fig. 4. The variation of the intensity profile of a truncated Gaussian beam with the radius of the circular aperture.

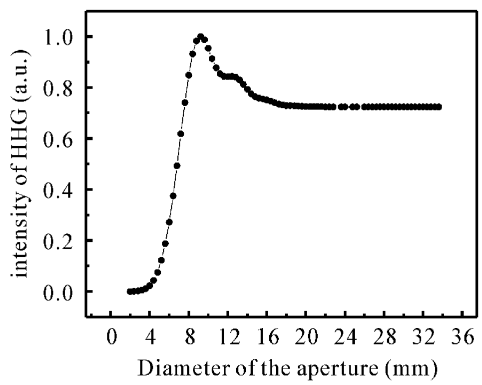

Fig. 5. The numerical simulated intensity of HHG at the plateau region versus diameter of the circular aperture using a Hankel transform.

well. When the diameter of the aperture is 9 mm, the intensity of HHG reaches its maximum value. We define $R = I_m/I_s$, namely, the ratio between the maximum and the final stable value of the intensity of HHG. We can get $R = 1.25$ in our experimental condition. This means the conversion efficiencies of high-order harmonics generated by the truncated Gaussian beams are higher than those of pure Gaussian beams. Because the radius of the circular aperture is much smaller than the waist of the fundamental beam when the intensity reaches its maximum, a part of pumping laser-pulse energy is lost. Consequently, the conversion efficiencies of the truncated Gaussian beam would be much higher in the case of pulses with equal energy content.

In conclusion, we have carried out an experimental investigation on HHG processes with truncated Gaussian beams. At a certain distance between the focus and the gas nozzle, the truncated Gaussian beam would enhance evidently the harmonic conversion efficiencies. The result is interpreted using the theory of Hankel transform. The simulated results fit the experimental ones well.

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