High-order harmonic generation with an annular laser beam

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High-order harmonics have been generated by the use of an annular laser beam. The nonlinearity of harmonic production and the shorter wavelengths involved cause the harmonics to emerge strongly peaked on the laser axis. Thus the harmonics emerge from the focus inside the missing portion of the laser beam. This permits the laser to be blocked by an aperture that passes the harmonics.

High-order harmonics have been studied during the interaction of intense lasers with noble gases. Harmonics with orders in excess of 100 and wavelengths less than 10 nm have been observed.[1–3] The development of a plateau[4–6] in the harmonic conversion efficiency for harmonics with orders of ≥9 suggests that the high-order harmonics may rival synchrotron light sources as a source of coherent vacuum-ultraviolet radiation with high spectral brightness (see Ref. 7 for an overview).

Harmonics created in a laser focus are emitted in the same direction as the propagating laser.[3,8,9] To utilize the harmonic light or, indeed, to observe it, it is advantageous to separate the harmonics spatially from the intense laser beam. Until now this has been done by the insertion of a grating in the beam path after the focus so that the light is redirected according to wavelength. Except for the highest harmonics, filtering the light is difficult because of the lack of suitable materials. In either case the grating or filter must be placed sufficiently far from the focus to ensure that the laser does not damage the surface.

We have demonstrated an alternative approach for eliminating the laser light from the path of the harmonic light. Harmonics produced by a laser that is axially peaked at its focus and annular in the far field emerge axially peaked. They can then be separated from the laser by an annular mirror. The requirements for the laser are that its field profile before focusing be annular and uniphase. This type of profile can be produced from a diffraction-coupled unstable resonator or by the placement of a central block in an axially peaked laser. It is important to note that a nonuniphase annular beam, such as a TM_{01}^* mode, will not have an axially peaked focus and will be unsuitable for this technique.

In our experiments the center of the laser beam was blocked before the focus lens, creating a doughnut-shaped beam. Figure 1 shows a diagram of the setup. At the focus the hole in the beam fills in to form a strong central peak surrounded by less intense rings. As the beam emerges again from the focus, the doughnut shape reappears. Because harmonic generation is a nonlinear process and because the harmonics have shorter wavelengths than the fundamental the harmonics tend to emerge close to the beam axis, similar to those produced with a usual Gaussian laser focus. After the focus an aperture can be placed in the beam that blocks the laser light but permits the harmonics to pass through its center. Following the aperture additional optical devices, such as gratings, filters, and mirrors, can be used freely without concern for damage by the laser. This permits these devices to be situated much closer to the region of harmonic production.

We prepared the doughnut-shaped beam by placing a 1.2-cm circular block in a collimated 2.1-cm Gaussian laser beam (diameter to $1/e^2$ intensity points). The laser wavelength is 1.054 μm. (The laser was described elsewhere.[10,11]) The block was positioned before a lens at a distance equal to the focal length (150 cm). Thus at the focus of the lens the field distribution is determined by a Fourier transform of the field distribution at the block.[12] The far-field pattern that emerges from the field distribution at the focus is again a clear image of the block.[12] Figure 2(a) shows an image of the laser measured at the focus. A strong peak occurs at the center, surrounded by less-intense rings. (Only one of the rings is strong enough to be seen in the image.) Figure 2(b) shows an image of the far-field pattern after the focus. The units on this image are those appropriate to the dimensions of the actual block. The four small lines are images of the suspension wires holding the block in place. The diameter of the block was chosen so as to remove half of the energy in the beam, reducing the peak intensity at the focus by 50%. It can be shown that, for a Gaussian beam, the peak intensity in the focus is reduced by exactly that fraction of energy removed by the block.

Because harmonic generation is a nonlinear process the radial distribution of harmonic light created at the focus is different from that of the laser beam. In particular, the amount of harmonic light generated in the rings at the laser focus is negligible compared with the harmonic light generated in the

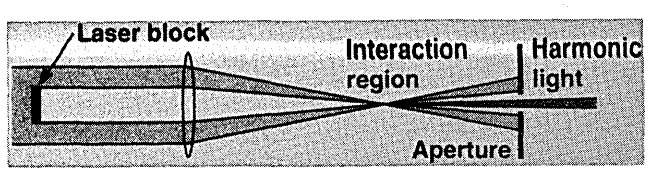

Fig. 1. Setup used to create a doughnut-shaped beam.

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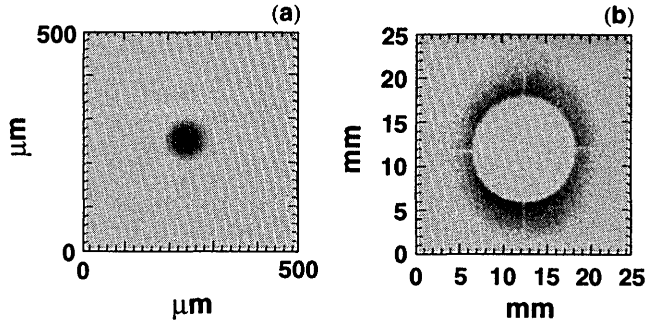

Fig. 2. Measured distribution of the doughnut-shaped beam (a) at focus and (b) after focus.

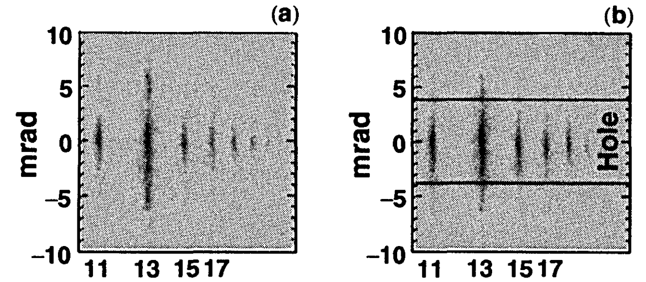

Fig. 3. Far-field angular profile of high-order harmonics created at the focus of (a) a Gaussian beam and (b) the doughnut-shaped beam.

central peak. Thus the harmonic conversion process behaves as a spatial filter similar to a small pinhole that blocks everything but the central peak. Without the rings in the focus, the doughnut shape is not formed in the far field. In addition, a shorter wavelength causes the harmonic light to emerge from the focus in a cone narrower than the laser.

The high-order harmonics were generated in a 1-Torr, 1-mm-thick distribution of Xe positioned at the laser focus.[13] The far-field angular profiles of the harmonics were observed both with and without the block positioned in the beam path. Figure 3(a) is an image showing the angular distribution of a number of harmonic orders generated with a Gaussian beam (no block inserted). Each line shows along its length the angular distribution of a given harmonic. Approximately 20 images were averaged together to create this picture. The transmission grating detector used to record the harmonic profiles was described elsewhere.[8,9] The peak laser intensity was approximately 7×10^{13} W/cm^2, with a pulse duration of 1.7 ps. The harmonics are brightest near the laser axis, though less-intense wings occur on the harmonics at wider angles. The wings result from intensity-dependent phase variations in the laser focus that are due to the dipole response of the atoms to the laser.[9,14]

Figure 3(b) is an image similar to that of Fig. 3(a), but the block was placed in the laser path. Again, approximately 20 images were averaged together to create this picture. The laser energy was doubled to keep the peak intensity at the focus the same as before. The angular width of the hole in the laser beam is indicated in the figure. As expected, the angular widths of the harmonics are similar with or without the beam block. The broad wings on the harmonics are wider than the hole; however, because they result from phase interferences[9,14] it may be desirable to remove them to improve the coherence of the harmonic beams for some applications. In any case the bright central portions of the harmonics lie well within the hole in the laser light.

We can compare the experimental observations with some simple calculations. Figure 4(a) shows the laser intensity distribution at the focus calculated for the conditions of the setup described above (solid curve). The radius is expressed in terms of the undisturbed Gaussian beam waist w_0, which for our focusing geometry is 50 μm. The dashed curve in Fig. 4(a) shows the laser focal distribution raised to the 11th power. This is representative of a strongly nonlinear process such as that of harmonic generation. For the dashed curve the rings are no longer important. The calculated far-field profiles of the two distributions of Fig. 4(a) are shown in Fig. 4(b). The radius is expressed in terms of the undisturbed Gaussian beam waist at a distance z after the focus. The far-field pattern of the dashed curve is calculated based on a wavelength of $\lambda/11$, which corresponds to the 11th harmonic of the fundamental. As the figure shows, the harmonic profile lies within the blocked portion of the laser beam, in agreement with the experimental results.

This technique for separating the laser from the harmonic light can be useful when it is desired to remove the laser soon after the focus, where the light is too intense for the optical surfaces. In this case the block can be positioned in front of the lens in such a way as to cause an image of the block to occur at the location of the aperture. Another potential application of this technique is to use a mirror with a hole drilled through it for the aperture in Fig. 1. Thus the laser energy might be recirculated through an amplifier to create harmonic pulses at a high repetition rate. A general concern is that the wave front of the laser may become distorted in the focus because of the presence of ionized free electrons. This might cause some bleeding of laser energy into the hole at the beam center and pose a limitation for some applications.

In summary, we have produced, for the first time to our knowledge, centrally peaked high-order harmonics with an annular laser beam focused into a thin gas target. This permits the laser pulse to be

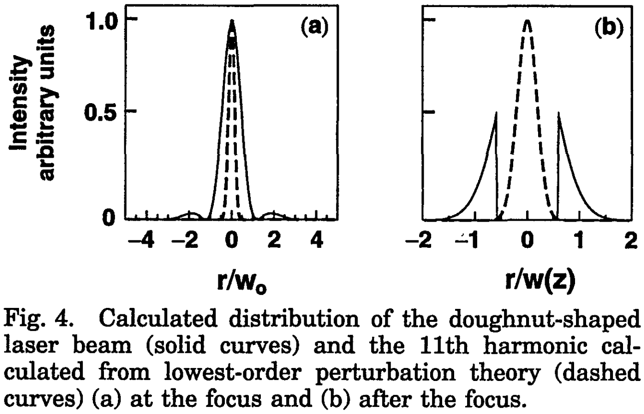

Fig. 4. Calculated distribution of the doughnut-shaped laser beam (solid curves) and the 11th harmonic calculated from lowest-order perturbation theory (dashed curves) (a) at the focus and (b) after the focus.

separated from all the high-order harmonics with an annular aperture.

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References

1. J. J. Macklin, J. D. Kmetec, and C. L. Gordon III, Phys. Rev. Lett. **70,** 766 (1993).
2. A. L.'Huillier, M. Lewenstein, P. Salieres, Ph. Balcou, M. Yu. Ivanov, J. Larsson, and C. G. Wahlstrom, Phys. Rev. A **48,** R3433 (1993).
3. R. A. Smith, J. W. G. Tisch, M. Ciarrocca, S. Augst, and M. H. R. Hutchinson, in *Super-Intense Laser Atom Physics,* B. Piraux, ed. (Plenum, New York, 1993).
4. A. L'Huillier, K. J. Schafer, and K. C. Kulander, Phys. Rev. Lett. **66,** 2200 (1991).
5. A. L'Huillier, P. Balcou, and L. A. Lompré, Phys. Rev. Lett. **68,** 166 (1992).
6. A. L'Huillier and Ph. Balcou, Phys. Rev. Lett. **70,** 774 (1993).
7. P. Corkum and M. Perry, eds., *Short Wavelength V: Physics with Intense Laser Pulses,* Vol. 17 of OSA Proceedings Series (Optical Society of America, Washington, D.C., 1993).
8. S. Augst, D. D. Meyerhofer, J. Peatross, and C. I. Morre, in *Short-Wavelength Coherent Radiation: Generation and Applications,* P. H. Bucksbaum and N. M. Ceglio, eds., Vol. 11 of OSA Proceedings Series (Optical Society of America, Washington, D.C., 1991), pp. 23–27.
9. J. Peatross and D. D. Meyerhofer, Bull. Am. Phys. Soc. **38,** 1770 (1993).
10. P. Maine, D. Strickland, P. Bado, M. Pessot, and G. Mourou, IEEE J. Quantum Electron. **24,** 398 (1988).
11. Y.-H. Chuang, D. D. Meyerhofer, S. Augst, H. Chen, J. Peatross, and S. Uchida, J. Opt. Soc. Am. B **8,** 1226 (1991).
12. M. Born and E. Wolf, *Principles of Optics,* 6th ed. (Pergamon, Oxford, 1980), Chap. 8, p. 370.
13. J. Peatross and D. D. Meyerhofer, Rev. Sci. Instrum. **64,** 3066 (1993).
14. J. Peatross, "The far-field angular distribution of high-order harmonics produced in light scattering from a thin low-density gas target," Ph.D. dissertation (University of Rochester, Rochester, N.Y., 1993).