Single-beam, ponderomotive-optical trap for free electrons and neutral atoms

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A ponderomotive-optical trap for energetic free electrons has been generated with a single, high-peak-power laser beam. The focal region consists of an intensity minimum at the center of the focus, with increasing intensities in all directions. The focus can be generated with a two-zone binary phase plate, or with a novel, coaxially segmented wave plate. This scheme can also be used to trap neutral atoms.

Neutral atoms and free electrons are both acted upon by forces proportional to the gradient of the laser intensity. The ponderomotive force accelerates electrons toward the intensity minimum,[1] whereas neutral atoms can be accelerated in either direction depending on the sign of the laser detuning.[2] This allows atoms to be trapped in a centrally peaked laser focus.[3] However, they tend to "boil" out of the trap owing to their strong interaction with the field.[4] Electrons are always accelerated away from a centrally peaked laser focus. At high intensities, electrons injected into the field by ionization with low energies can be accelerated to energies of 100 keV or more.[5] These electrons leave the focus rapidly, limiting their interaction time with the intense field. So in either case (free electrons or neutral atoms), one could achieve confinement by creating a local minimum in intensity at the focus. For free electrons, the ponderomotive force would push the electrons to the center of the trap. For neutral atoms, as long as the field is tuned above resonance, the dipole force would drive the atoms toward the minimum. Ponderomotive trapping has been proposed in the past,[6,7] and specific laser-based methods of trapping electrons in the radial direction have been described.[8,9] These schemes would not confine electrons in the axial direction. Multiple-beam "dark" atom traps have also been realized.[10] It is the purpose of this Letter to present, for the first time to our knowledge, a scheme to trap either free electrons or neutral atoms in three dimensions with a single beam and a measurement of the trapping focus.

It is well known that phase modulation in the near field of a beam will result in far-field amplitude modulation with little loss in total energy.[11] This concept has led to the design and manufacture of complex phase plates that alter the focal spot of a laser beam.[12,13] An intensity minimum at the focus can be created with a simple two-level phase plate that contains only two zones. According to Babinet's principle, one can combine the individual fields generated from complementary screens that are arriving at some point to find the unobstructed field.[14] Choosing from an incident Gaussian field a π-shifted disk and an unshifted annulus that each contain half of the electric field creates a region of zero intensity at the focus. The magnitudes of the individual fields are equal but their phases are opposite, resulting in complete destructive interference. The intensity increases in all directions about this minimum. By changing the size of the π-region, or by changing the incident beam size, one can tune the depth of the minimum. One could make such a phase plate by using photolithographic techniques[15] or by manufacturing the segmented half-wave plate as described below.

Figure 1(a) shows the calculated focal-intensity distribution of a Gaussian beam focused through a phase plate with a π-region diameter of 1.65 w (where w is the $1/e^2$ radius in intensity of the incident beam). This results in a π-phase shift for half of the incident field. The intensity is normalized to the peak intensity in the absence of the phase plate. The r and z positions are normalized to the unaltered beam waist, w_0 ($1/e^2$ radius), and the unaltered beam Rayleigh range, z_0, respectively. Figure 1(b) shows a contour plot of the trapping region. There is an exact zero intensity at the center of the focus, with intensity walls ranging from ~8% to ~30% (of the unaltered peak intensity) in all directions. The trapping region

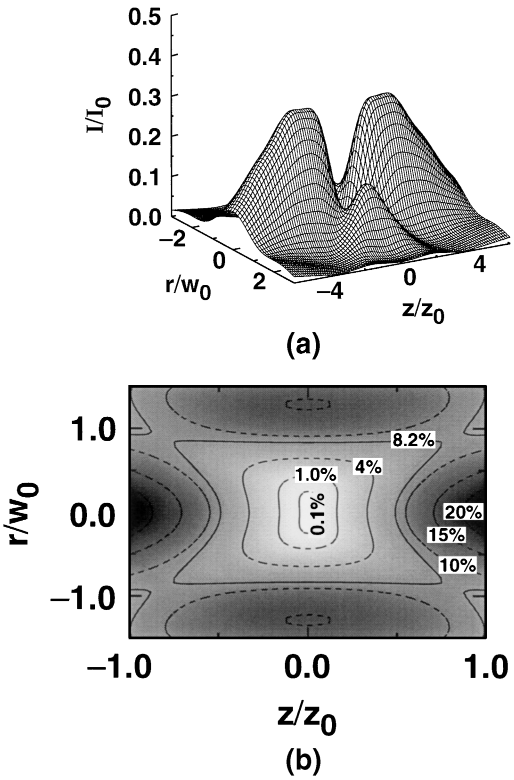

Fig. 1. (a) Computer-generated surface-plot trapping focal region with zero intensity at the center (π-region diameter 1.65 w). (b) Contour plot of the trapping region.

has a volume of complete trapping of $\sim 2 w_0^2 z_0$. One can vary the minimum intensity at the center of the trap by changing the size of π region (or by changing the size of the incident beam). Figure 2(a) shows the calculated focal distribution for a Gaussian beam that is incident upon a phase plate with a π-region diameter of 2.20 w. Figure 2(b) shows a contour plot of the trapping region. In this case the bottom of the trap is $\sim$17% of the unaltered beam peak intensity, and the trap walls range from $\sim$24% to $\sim$50%. The trapping volume is $\sim w_0^2 z_0$.

In the computer code used for calculating the focal regions, the incident phase front is assumed to be planar and the focusing lens is assumed to be free of aberrations. A beam in any high-power laser system can accumulate wave-front error from misaligned, damaged, or aberrated optics or from uneven amplification. Although moderate aberrations do not destroy the trap, highly aberrated beams will not create effective traps. Similar trapping regions can be generated with super-Gaussian or flat-top incident beam profiles.

A trapping focal volume was created in the laboratory by use of a segmented $\lambda/2$ plate, which is equivalent to a two-level phase plate. A $\lambda/2$ plate is built such that there is a retardation of π phase between two orthogonal incident polarizations. If part of the incident beam travels through the plate as a fast wave and the other part travels as a slow wave, a π-phase shift is created between the two portions. To accomplish this, we cut a 4-cm disk from the center of an 8-cm-diameter mica $\lambda/2$ plate. The disk and the annulus were then mounted individually upon crosshairs and aligned with the beam path, as shown in Fig. 3. In the figure the laser is polarized in the vertical direction and the annulus is arranged such that its e axis is vertical, whereas the disk's o axis is vertical. This results in an added π phase for the central portion of the incident field. The size of the disk was chosen such that approximately half of the incident electric field passed through it. This results in a near-zero intensity at the center of the focus. By rotating the two pieces as a unit, one can rotate the polarization direction of the incident beam without introducing additional optics or changing the shape of the focal region. The depth of the trap can be tuned by rotation of the central disk away from 90° with respect to the annulus. This results in a polarization rotation of the inner portion of the beam, which will put some of the field into the noninterfering orthogonal polarization, thereby filling in the minimum. The extreme case of this is when the disk is rotated a full 90°, back to its original position, which produces an ordinary, centrally peaked focus.

The altered focal spot was created with the waveplate arrangement combined with a 212-cm focal-length lens and was imaged with a CCD camera

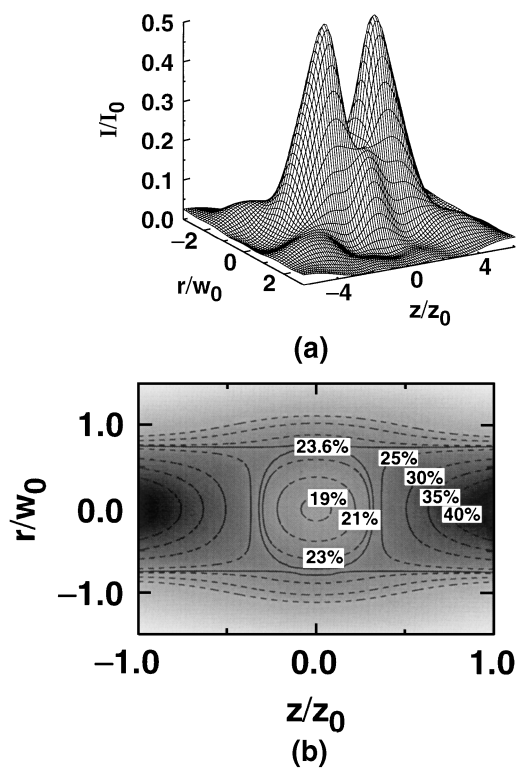

Fig. 2. (a) Computer-generated surface-plot trapping focal region with 17% intensity at the center (π-region diameter 2.20w). (b) Contour plot of the trapping region.

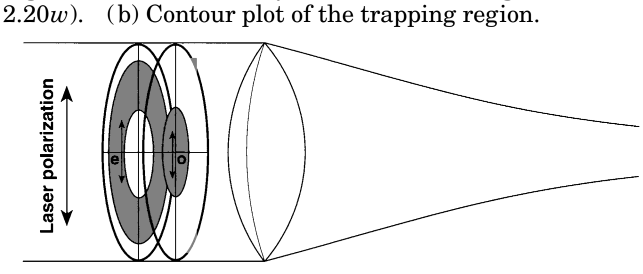

Fig. 3. Experimental configuration of a segmented waveplate technique for generating a trapping focal region.

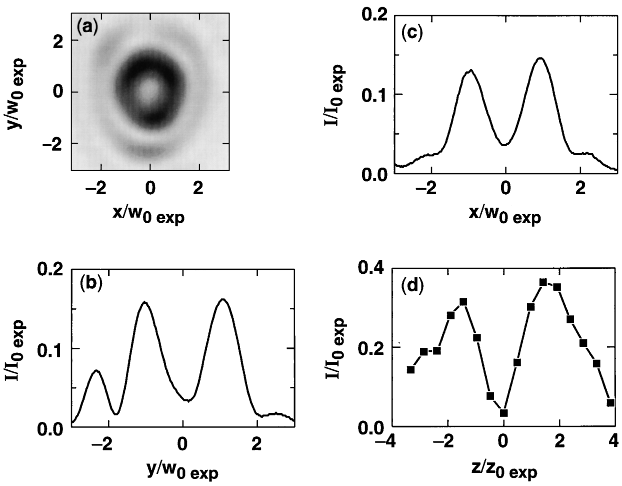

Fig. 4. Experimental results: (a) Image of the altered focal spot at $z = 0$ (best focus). (b) Lineout in the y direction at best focus. (c) Lineout in the x direction at best focus. (d) Intensity at $r = 0$ as a function of z. All axes are normalized to experimentally determined values for the unaltered beam [spot size (w_0 exp) for the x and the y positions, Rayleigh range (z_0 exp) for the z positions, and unaltered beam peak intensity (I_0 exp) for intensity values].

coupled to a 10× microscope objective. We moved the camera–objective combination together to map out the focal region. A single laser shot was taken at each position, and each image was minimally smoothed and background subtracted. The measurements were taken with ~2-ps, ~40-mJ, and 1.053-μm laser pulses from a chirped-pulse-amplification laser system at a repetition rate of 1 shot/20 s.[16] The altered focal spot generated by the full amplifier chain (capable of producing >1-J pulses at 1 shot/3 min) was measured at the best focus position to confirm that the trap could be generated at full energy. Figure 4(a) shows an image of the beam at $z = 0$ with the wave-plate arrangement set to 90° between the inner and the outer regions. The spot exhibits a near-zero intensity at the center, with increasing intensities in all directions. Figures 4(b) and 4(c) show the lineouts at $z = 0$ in the y and the x directions. The x and the y axes are normalized to the experimentally determined beam waist of the unaltered beam, which is approximately 1.5× diffraction limited. The altered focal spot has a well-defined minimum. Figure 4(d) shows the intensities of the beam at $r = 0$ as a function of z. The intensities of Fig. 4 are normalized to the peak intensity of the unaltered beam. This experimentally obtained distribution exhibits a local minimum in intensity at the origin along all three dimensions, making it a highly suitable focal region for ponderomotive trapping.

An immediate application of this altered focal region is the investigation of relativistic second-harmonic generation from free electrons. For our current arrangement for studying high-field atomic physics (focal-spot-size $w_0 \sim 5\ \mu$m, $\tau_{\mathrm{FWHM}} \sim 2.0$ ps, $E \sim 2$ J),[5] a trap could be generated with a peak intensity at the trap minimum of $\sim 2.0 \times 10^{17}\ \mathrm{W/cm^2}$ and a trapping volume of $\sim 3500\ \mu\mathrm{m}^3$. If the vacuum chamber is backfilled with 1.0 mTorr of xenon, there will be $\sim 10^6$ electrons with 20 keV of quiver energy, each localized at the peak of the pulse. This should provide a detectable source of second-harmonic generation.[17]

In summary, we have produced, for the first time to our knowledge, a tunable, single-beam, three-dimensional, ponderomotive-optical trap for free electrons with a high-peak-power laser system. We have presented two possible schemes for creating such a focal region, along with experimental results from a novel, coaxially segmented wave-plate approach. Either method is adaptable to a wide range of laser systems, from continuous wavelength to ultrashort pulse systems.

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