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Achromatic lenses for atoms using velocity-dependent light-induced potentials

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Abstract

We propose achromatic lenses for atoms based on the induced dipole force in near-resonant spatially varying light fields. The velocity dependent focal length of “standard” dipole force lenses is partly compensated by making the detuning velocity-dependent through the Doppler effect. For instance, for a longitudinal velocity distribution with a relative width, $\Delta v/v \approx 0.2$ a variation in focal length of less than 3% can be achieved both for thin and for thick lenses. This is an order of magnitude smaller than previous lenses based on the dipole force, and hence such lenses could have interesting applications in atom microscopes and atom lithography.

Keywords: Focusing of atoms; Induced dipole lenses

PACS: 32.80.-t; 42.vk; 41.85.-p

In the fast developing field of atom optics [1,2] one seeks to create optical elements and systems for atoms, such as lenses, mirrors, gratings, and interferometers. Atom lenses with good focusing properties, which are the topic of the present paper, are especially interesting for the realization of atom microscopes or atom lithography [3,4]. Compared to lenses for light, however, atom lenses generally have a relatively high degree of dispersion with respect to the (de-Broglie) wavelength. Since the de-Broglie wavelength is inversely proportional to the atomic velocity the performance of the optical elements are highly dependent on the velocity distribution in the atomic beam. This is the case for lenses constructed so far using light fields

[3–10], for Fresnel zone-plates [11], and for electro- and magneto-static fields [12,13].

An obvious way to get around the dispersion problem would be to prepare a nearly monochromatic atomic beam by using highly supersonic sources, velocity selection, or by using laser cooling to compress the velocity distribution. Here we advocate a different approach, namely constructing optical elements which are less dispersive, similar to achromatic lenses commonly used in light optics. Previously, achromatic lenses for atoms based on the radiation-pressure force [7] as well as a combination of a Fresnel zone plate and an electro-/magneto-static lens has been proposed [14], but not so far been demonstrated. In the present paper we consider the possibilities of constructing simple achromatic singlet lenses using light-induced dipole forces.

Focusing of a neutral atomic beam by induced

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dipole forces was first reported by Bjorkholm et al. [5] in 1978. They demonstrated 2D focusing of an atomic beam by a co-propagating Gaussian (TEM_{00}) laser mode which was negatively detuned. Later lenses based on co- or counterpropagating TEM_{10}^* (donut mode) traveling laser beam have been proposed, but not tested [6,8,9]. More recently, atom focusing by standing-wave light fields has been investigated experimentally, both in the thin [10] and the thick [3,4] lens regime. In Ref. [10] an atomic beam was focused down to 4 μm in one dimension, limited mainly by diffraction. In the experiment by McClelland et al. [4] a periodic set of cylindrical thick lenses was created by a standing light wave. The focused lines were reported to be only 65 nm wide (FWHM), limited by chromatic aberration due to the use of a thermal atomic source. Our solution to the problem of chromatic aberration could therefore lead to even narrower focusing.

An atom moving in an inhomogeneous light field that is nearly resonant with an atomic transition, is subjected to a force due to the spatially varying coupling between the atom and the field. This force, sometimes referred to as the induced dipole force, is suitable for the creation of atom lenses if it can be approximated by a harmonic force around certain points x_0 in space: $F(x) \approx -\kappa(x - x_0)$, where κ is the spring constant. We distinguish here two limiting cases, denoted as “thin” and “thick” lenses. In the thin lens limit the atom interacts with the light field during a time τ_{int} , short compared to f/v , where f is the focal length and v the velocity along the beam axis. In this regime, also called the Raman-Nath regime, the interaction with the light field is well approximated by an instantaneous momentum kick. In the thick lens limit, the interaction time is of the order of f/v so that focusing takes places close to where the atom leaves the light field. In this regime the equation of motion inside the light field has to be solved.

For a thin lens, taking the y -axis as the atomic beam axis and neglecting transverse atomic movement prior to entering the light field, the focal length can be determined from the geometrical condition $\Delta v_x/v_y = -(x - x_0)/f$, where Δv_x is the atomic velocity along the x -axis after the interaction. With $\Delta v_x = F(x)\tau_{\text{int}}/m = -\kappa(x - x_0)L_{\text{int}}/v_y m$, where L_{int} is the interaction length, and m the atomic mass, one finds that $f = v_y^2 m / \kappa L_{\text{int}}$. The focal length is thus

independent of x , but quadratically dependent on the velocity v , and hence leads to chromatic aberration.

In the case of a thick lens, an initially collimated beam will be focused after an interaction time τ_{int} equal to one quarter of the oscillation period τ_{osc} of the harmonic potential. The focal length in this case is $f = v_y \tau_{\text{osc}} / 4 = (\pi/2) v_y \sqrt{m/\kappa}$, and seen also to be chromatic, although only linearly.

The region around the nodes (anti-nodes) of a one-dimensional standing-wave (SW) light field at frequency ω_L can serve as a lens for a beam of two-level atoms with transition frequency ω_0 if the detuning $\delta = \omega_L - \omega_0$ is positive (negative). Assuming adiabatic following of the atom-light field coupling and assuming that no spontaneous emission takes place, the dressed-state picture gives the following interaction potential [15]:

$$U(x) = \frac{\hbar\delta}{2} \sqrt{1 + (\Omega_0^2/\delta^2) \cos^2 kx}. \quad (1)$$

Here $\Omega_0 = dE_0/\hbar$ is the maximum Rabi frequency in the standing wave, d the transition dipole moment, E_0 the field amplitude, and k the norm of the wave vector. Making a harmonic approximation of $U(x)$ around the nodes (anti-nodes) for positive (negative) detunings, we find the following spring constants κ

$$\kappa = \frac{\hbar\Omega_0^2 k^2}{2\sqrt{\delta^2 + \Omega_0^2}}, \quad \delta < 0, \quad (2)$$

$$\kappa = \frac{\hbar\Omega_0^2 k^2}{2\delta}, \quad \delta > 0. \quad (3)$$

Like the achromatic lens based on the radiation-pressure force mentioned in Ref. [7], our proposal for compensating the chromaticity of the dipole lenses uses the Doppler effect to make the detuning dependent on the atomic velocity. The effective (Doppler-shifted) detuning δ' is then

$$\delta' = \delta - k'v, \quad (4)$$

where k' is the component of the wavevector along the velocity v . For positive detuning, chromatic aberration is compensated to first order in v around a central velocity v_0 if we choose

$$\delta = \frac{3}{2} k' v_0. \quad (5)$$

With Eq. (5) fulfilled, the focal lengths for thin and thick lenses become

$$f(\xi) = \frac{mv_0^2}{\kappa(v_0)L_{\text{int}}} (1 - 3\xi^2 - 2\xi^3) \quad (6)$$

and

$$f(\xi) = \frac{\pi}{2} \sqrt{\frac{m}{\kappa(v_0)}} v_0 \sqrt{1 - 3\xi^2 - 2\xi^3}, \quad (7)$$

respectively, where we introduced the normalized relative velocity $\xi \equiv (v - v_0)/v_0$. In Fig. 1, the relative focal length, $f(\xi)/f(0)$, of a standard SW thin lens, $(1 + \xi)^2$, and of a corresponding achromatic lens, $1 - 3\xi^2 - 2\xi^3$, are compared. For velocities within 10% of the central velocity ($-0.1 \leq \xi \leq 0.1$) the variation in focal length for the uncompensated SW is about 40%, whereas it is less than 3% for the velocity-dependent light potential. The same degree of improvement is found for the thick lens. This large suppression of the chromatic aberration gets even more pronounced for narrower velocity distributions.

For negative detunings it is in principle also possible to obtain velocity-compensated dipole lenses, but in practice spontaneous emission poses a problem. In order to make the first-order term in Δv (or equivalent ξ) vanish in the focal-length expressions, the detuning δ has to be at least ≈ 5 times the maximum Rabi frequency Ω_0 and $k'v \geq 4\Omega_0$. For thermal atomic beams the latter condition leads to rather small Rabi frequencies while the former leads to rather large detunings. Using a dipole-allowed atomic transition, for a thick lens the oscillation period of the potential will

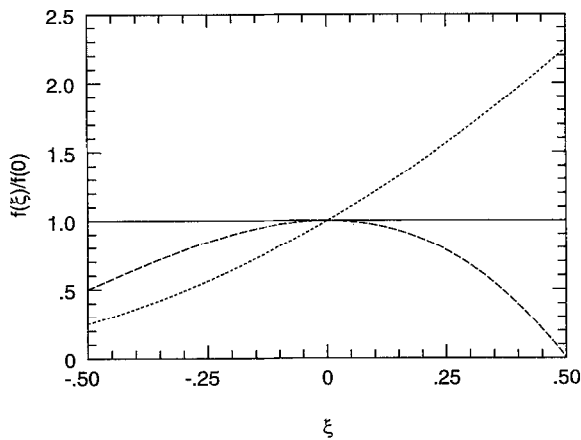


Fig. 1. The relative focal length of a normal SW thin lens (dotted line) and a corresponding achromatic lens (dashed line) as a function of the relative velocity displacement $\xi \equiv (v - v_0)/v_0$. The focal length is normalized to the value at $\xi = 0$.

then typically get larger than the lifetime of the upper atomic state so that spontaneous emission becomes a problem. The same is true for a thin lens if a reasonably short focal length (≤ 10 cm) is desired. A more detailed analysis of the effect of spontaneous emission as well as other aberration effects is in progress.

In Fig. 2 two possible experimental realizations of achromatic lenses for one-dimensional focusing are shown. In Fig. 2a a velocity-dependent detuning is realized in a standing light field along the x -axis created by two traveling light waves, whose propagation directions are given by two angles α and β . The k -vectors of the two traveling waves make an angle $\pi - 2\alpha$, so that

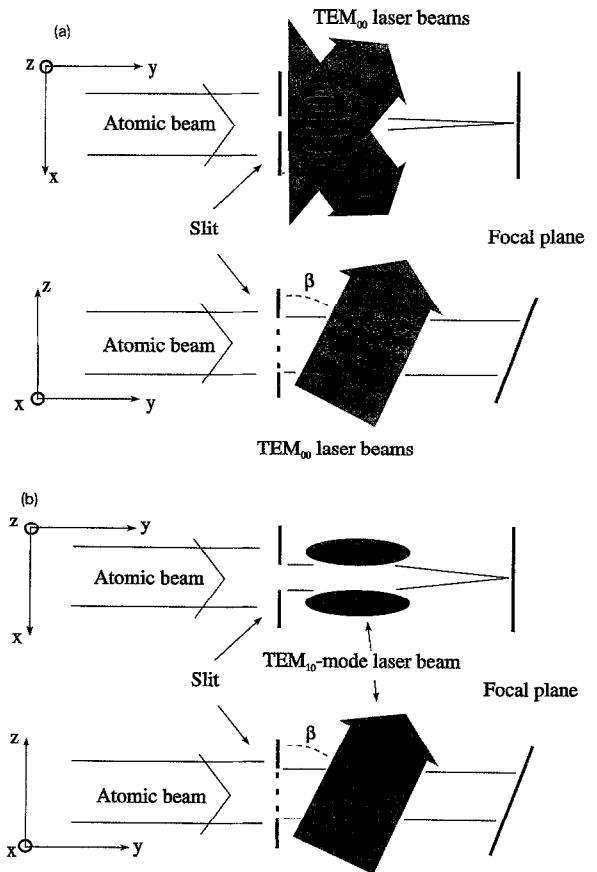


Fig. 2. (a) Proposed setup for a SW achromatic lens. The angle α is defined as $\pi/2 - \gamma/2$, where γ is the angle between the two wave vectors. β is the angle between the plane spanned by the two wave vectors and the x - z -plane. (b) Proposed setup for a TEM_{01} mode achromat. Here β is the angle between the z -axis and the wavevector.

the standing wave has a period $\pi/k \cos \alpha = \lambda/2 \cos \alpha$. The atomic beam makes an angle β with the normal to the plane spanned by the two k -vectors. When the polarization of the two electrical fields is identical and we choose a node in $x = 0$, the total electrical field reads

$$E_{\text{tot}} = E_0 \cos(\omega_L t - ky \sin \alpha \sin \beta - kz \sin \alpha \cos \beta) \times \cos(kx \cos \alpha), \quad (8)$$

where ω_L is the laser frequency of the two fields and E_0 the total field amplitude. If an atom is moving along the y -axis with a velocity v , then the effective detuning of the SW light field is $\delta' = \delta - kv \sin \beta \sin \alpha$, i.e. in the form of Eq. (4). The focusing properties of this field in the thin and thick lens approximation can be found from Eqs. (6) and (7) with $\kappa(v_0) = \hbar \Omega_0^2 k^{*2} / kv_0 \sin \alpha \sin \beta$, where $k^* = k \cos \alpha$. Since the condition given by Eq. (5) contains both angles α and β , there is a certain freedom in the choice of α , i.e. the standing wave period. This is especially useful when the reduction of other aberrations is of issue.

An even simpler achromatic dipole lens can be constructed with the use of TEM₀₁ (Hermite-Gaussian) laser beams, as shown in Fig. 2b. With the indicated angle β , the effective detuning becomes $\delta' = \delta - kv \sin \beta$. In this case the size of the lens opening is proportional to the waist parameter perpendicular to the atomic beam. Because of its simplicity a combination of two such lenses in series seems particular interesting for focusing in two dimensions. It should be noted that the focal plane of such a 2D achromatic lens is not perpendicular to the atomic beam direction, but parallel to the plane spanned by the k -vectors. This should not lead to experimental difficulties as long as the detector plane coincides with the focal plane.

For 2D-focusing, the geometry of Fig. 2b has the advantage that the polarizations used for the two TEM₀₁ beams can be chosen the same (orthogonal to the two wave vectors). In combination with optical pumping prior to focusing, this could eliminate the problem of different focal lengths for atoms in various magnetic sublevels due to unequal Clebsch-Gordan coefficients.

In order to show that other aberrations do not necessarily dominate chromatic errors, in Fig. 3 simulations of atomic beam profiles in the focal plane are presented for experiments with thin lenses. The solid curve corresponds to an achromatic lens, while the dashed line

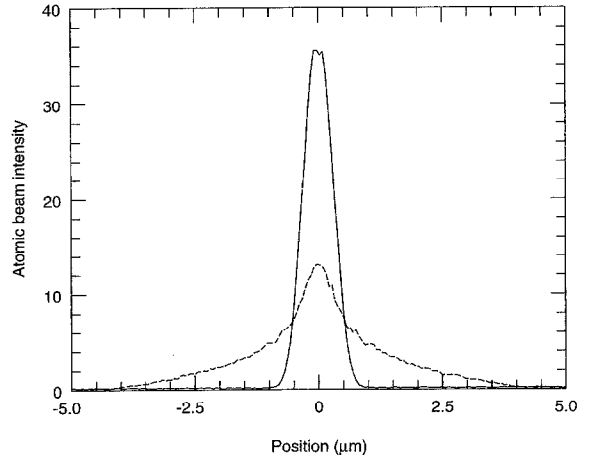


Fig. 3. Dressed-state Monte Carlo simulations of the atomic beam intensity at the focal plane as a function of the position from the beam center for a realistic focusing experiments with metastable helium. The solid line represent the results with a achromatic thin lens, while the dashed line corresponds to a normal SW lens. The intensity is normalized to the intensity at the lens. Experimental parameters are given in the text.

refers to a standard thin dipole lens with the same focal length. In the calculation we have used a dressed-atom Monte-Carlo simulation [16] including the effect of spontaneous emission for the atom-light field interaction and used beam parameters realistic for the metastable helium beam apparatus in Constance [10], i.e. $\Delta v/v_0 = 0.2$ and $v_0 = 1800$ m/s. The distance from the atomic source to the dipole-lens setup is set to 1 m and the focal length is chosen to be about 15 cm. The source slit is chosen to be $2 \mu\text{m}$ and a $30 \mu\text{m}$ slit just in front of the lens limits the spherical aberration. The two traveling laser beam are assumed gaussian in the direction of the atomic beam with a waist of 2 mm and with a maximum Rabi frequency $\Omega_0 = 340\Gamma$, where Γ is the decay rate of the $1s2p^3P_{0,1,2}$ to the metastable state $1s2s^3S_1$. The angles α and β were chosen to be 89.85° and 30° , respectively, which gives a detuning $\delta = 245\Gamma$. In the simulation, the achromatic lens yield a threefold increase in the on-axis atomic intensity as compared to the normal chromatic lens. Furthermore, the original tophat profile of the source is better reproduced by the achromat, suggesting better imaging properties.

The achromatic lens proposed by Balykin et al. [7] rely on the radiation-pressure force, and hence inherently subjected to aberration due to the random re-

coil of spontaneous emitted photons. In contrast, for achromatic dipole lenses this effect

The limitation of our scheme for achromatic lenses lies essentially in the restriction given by Eq. (4) to choose the detuning for a given atomic velocity v_0 . As a consequence, for dipole-allowed transitions it is not possible to make short focal length lenses for slow atoms without getting problems with spontaneous emission and deviation from adiabatic following of the dressed-state potential given by Eq. (1).

In conclusion, we have presented simple schemes for creating dipole lenses for atoms that to first order are corrected for chromatic aberration, and hence out-perform standard dipole lenses when the relative velocity spread is smaller than ≈ 0.2 . Currently, investigations of achromatic doublets, i.e. systems consisting of two lenses, are in progress. In such a case, it is possible to construct achromats which also to second order are corrected for chromatic errors, and hence could be used for focusing even thermal beams without severe chromatic aberrations.

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