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

M. Drewsen, R.J.C. Spreeuw, J. Mlynek
Fakultät für Physik, Universität Konstanz, D-78434 Konstanz, Germany

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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

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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
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$_{20}$ (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 $\kappa$ 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 $\tau_{\text{int}}$ short compared to $f/\nu$, where $f$ is the focal length and $\nu$ 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 $f/\nu$ 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 $\Delta \nu_x/\nu_y = -(x - x_0)/f$, where $\Delta \nu_x$ is the atomic velocity along the $x$-axis after the interaction. With $\Delta \nu_x = F(x)\tau_{\text{int}}/m = -\kappa(x - x_0)L_{\text{int}}/\nu_y m$, where $L_{\text{int}}$ is the interaction length, and $m$ the atomic mass, one finds that $f = v_\gamma^2 m/\kappa L_{\text{int}}$. The focal length is thus independent of $x$, but quadratically dependent on the velocity $\nu_y$ and hence leads to chromatic aberration.

In the case of a thick lens, an initially collimated beam will be focused after an interaction time $\tau_{\text{int}}$ equal to one quarter of the oscillation period $\tau_{\text{osc}}$ of the harmonic potential. The focal length in this case is $f = v_\gamma \tau_{\text{osc}}/4 = (\pi/2) \nu_y \sqrt{m/\kappa}$, 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 $\omega_0$, can serve as a lens for a beam of two-level atoms with transition frequency $\omega_a$ if the detuning $\delta = \omega_a - \omega_0$ 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]:

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

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 $\kappa$:

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

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

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 $\delta'$ is then

$$\delta' = \delta - k'\nu,$$

where $k'$ is the component of the wavevector along the velocity $\nu$. For positive detuning, chromatic aberration is compensated to first order in $\nu$ around a central velocity $\nu_0$ if we choose

$$\delta = \frac{3}{2} k' \nu_0.$$  

With Eq. (5) fulfilled, the focal lengths for thin and thick lenses become
and
\[ f(\xi) = \frac{m v_0^2}{\kappa(v_0)} L_{\text{int}} (1 - 3\xi^2 - 2\xi^3) \tag{6} \]

respectively, where we introduced the normalized relative velocity \( \xi = (v - v_0)/v_0 \). 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 \( \Delta v \) (or equivalent \( \xi \)) vanish in the focal-length expressions, the detuning \( \delta \) has to be at least \( \approx 5 \) times the maximum Rabi frequency \( \Omega_0 \) 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 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 \( \alpha \) and \( \beta \). The \( k \)-vectors of the two traveling waves make an angle \( \pi - 2\alpha \), so that
the standing wave has a period \( \pi/k \cos \alpha = \lambda/2 \cos \alpha \).

The atomic beam makes an angle \( \beta \) 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

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

where \( \omega_L \) 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 \( \alpha \) and \( \beta \), there is a certain freedom in the choice of \( \alpha \), 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 TEM\(_{01}\) (Hermite-Gaussian) laser beams, as shown in Fig. 2b. With the indicated angle \( \beta \), 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 particularly 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 TEM\(_{01}\) 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 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., \( \Delta \nu/\nu_0 = 0.2 \) and \( \nu_0 = 1800 \text{ m/s} \). 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 \( \Gamma \) is the decay rate of the 1s\(^2\)2p\(^3\)P\(_{0,1,2}\) to the metastable state 1s\(^2\)s\(^3\)S\(_1\). The angles \( \alpha \) and \( \beta \) were chosen to be 89.85\(^\circ\) and 30\(^\circ\), respectively, which gives a detuning \( \delta = 245 \Gamma \). In the simulation, the achromatic lens yield a threfold 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-
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