Optimal profile for a Gaussian standing-wave atom-optical lens

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We have used a Gaussian standing-wave atom-optical lens to focus a thermal atomic beam. We examine the effect of variations in the intensity profile along the direction of the atomic beam on the performance of our atom-optical lens. For a constant focal-length atom-optical lens, we find that the resolution and contrast of the standing-wave lens are independent of the intensity profile. © 1997 Optical Society of America

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The use of a standing-wave (SW) atom-optical lens to focus a neutral atomic beam has recently become of interest because of its potential for high-resolution, high-contrast, and high-throughput lithography. Resolution in these atom-optical systems is proportional to the focal length of the SW lens, and improvements in resolution by reductions in this focal length are sought. In particular, we have demonstrated <15-nm resolution with contrast of at least 6:1 by focusing a thermal sodium atomic beam with a short-focal-length SW lens. The reduction in focal length is usually accomplished by reduction of the diameter of the SW beam, which, while improving resolution, reduces throughput. In this Letter we examine a scheme for improving resolution and contrast by exploiting the superficial similarity of a SW lens that is modifying the trajectories of an atomic beam and a gradient-index optical lens in which an inhomogeneous medium is used to redirect light rays. This similarity has led us to pursue improvements in the SW lens by manipulating the intensity profile along the direction of the atomic beam. For ease of comparison, we examine radically different intensity profiles that produce SW lenses with approximately the same focal length. Thus we delineate the optimum intensity profile for a SW lens that is focusing a thermal atomic beam to a specific level of performance.

The SW lens is usually pictured as a Gaussian SW with an intensity distribution \( I(x, z) = I_0 \cos^2(kx) \times \exp(-2z^2/\sigma^2) \). The \( 1/e^2 \) radius of the Gaussian beam is defined as \( \sigma \), and \( k = 2\pi/\lambda \) is the wave vector in the SW, where \( \lambda \) denotes the wavelength of the light (589 nm for sodium). The atomic beam propagates along the \( z \) direction and is focused onto a substrate placed at a position \( z = z_f \). The interaction between the induced atomic dipole and the electric field of the SW creates a series of potential wells, regularly spaced every \( \lambda/2 \) along \( x \). If the time for an atom to transit the SW in the \( z \) direction is equal to the time that an atom takes to reach the potential minimum in the \( x \) direction, then the atomic beam is focused into a series of lines on the substrate.

The sample is usually placed along the centerline of the SW beam, \( z_f = 0 \), and the detuning \( \Delta \) between the atomic resonance and the laser frequency and the peak intensity \( I_0 \) are chosen to satisfy this timing condition. The region over which the focusing occurs in the \( x \) direction is defined by the confocal parameter of the Gaussian beam, \( x_c = 2\pi\sigma^2/\lambda \).

In the dressed-state ansatz, for positive detuning \( \Delta \), the dynamics of the atom in the light field can be deduced from the eigenvalue corresponding to the weak-field seekers:

\[
U(x, t) = \frac{\hbar \Delta}{2} \left[ 1 + \frac{I(x, t) I_s}{I_0} \frac{2}{1 + \Delta^2/(\Gamma/2)^2} \right]^{1/2},
\]

provided that \( \Delta \gg \Gamma \). For linear polarization \( I_0 = 11.4 \text{ mW/cm}^2 \) for sodium at this wavelength, and the linewidth of the excited state \( \Gamma = 10 \text{ MHz} \). Using this potential and geometric optics, one can show that focal length of the SW lens can be given approximately as

\[
f = a \left( \frac{2}{\pi} \right)^{1/2} \frac{\hbar k}{P} \delta \left[ \frac{\Delta}{\Gamma} \right] \left[ 1 - \frac{1}{2} \phi \left( \sqrt{2z_f}/\sigma \right) \right],
\]

where we have assumed that \( \Delta \gg \Gamma \). In relation, \( P = I_0\sigma^2/2 \), \( \sigma \) is the momentum of the atom, and \( \phi \left( \sqrt{2z_f}/\sigma \right) \) is the complementary error function.

We used the form of the potential in Eq. (1) to numerically simulate focusing, subject to the particular experimental conditions; details of these calculations are described elsewhere. The longitudinal velocity of the atomic beam is assumed to have a Boltzmann distribution, as determined by the oven temperature of 672 K; the most probable velocity is \( \sim 860 \text{ m/s} \). With a detuning of \( \Delta = 1.7 \text{ GHz} \), the intensity in the simulations has been adjusted to yield the highest resolution, \( \sim 1.5 \times \) the intensity needed to focus optimally the most probable longitudinal velocity. The transverse velocities are assumed to have a Boltzmann distribution characteristic of a beam with a temperature of 25 \( \mu \text{K} \), consistent with polarization-gradient cooling. After following the time evolution through the SW lens, the final atom positions are discretized in 1-nm steps and summed. These results are shown as the dashed curves in Fig. 4. The linewidth is defined as the FWHM of the deposited line, and the contrast is the ratio of thickness in the center of the line to the thickness halfway between the lines.

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It can be seen from relation (2) that by adjusting the focal position $z_f$, the power, and the beam waist $\sigma$, we can achieve the same focal length under different intensity profiles. The power needed to focus optimally for $z_f = 0$ was experimentally determined to be $P = 8$ mW. From our simulation we find that to focus at $z_f = -\sigma/2$ we must increase the power by a factor of 5, whereas to focus at $z_f = +\sigma$ with a comparable focal length, we must decrease the power by a factor of 5.3 and reduce $\sigma$ by a factor of 2. A summary of the simulation results is shown in Fig. 1. The figure shows how both the power needed to achieve optimum focus and the deposited linewidth change as a function of $z_f/\sigma$ for a constant $\sigma$. From our simulations we also find that the relative changes shown in Fig. 1 are universal for all $\sigma$.

The ultrahigh-vacuum apparatus scanning tunneling microscope (STM) evaluations used in these experiments were described elsewhere. In these experiments the divergence of the atomic beam from a mechanically collimated oven at 673 K was reduced by use of optical molasses in a polarization-gradient configuration. Subsequently the atomic beam is focused by a SW lens with a modified Gaussian intensity profile.

To adjust the intensity profile we manipulated three parameters: the center of the SW relative to the edge of the sample, $\sigma$, and the power in the SW beam. The three profiles that we investigated are shown in Fig. 2. In all cases the SW beam was linearly polarized. Figures 3(a), 3(b), and 3(c) show three STM images of sodium gratings corresponding to the three different Gaussian intensity profiles shown in Figs. 2(a), 2(b), and 2(c), respectively. The deposition time in each case was adjusted so that the height of the sodium grains that form the lines was ~20 nm to accommodate the inability of the STM to retract dynamically more than 25 nm during a scan. The roughness along the edge of the lines indicates the 10–20-nm grain size of our deposited films, not the roughness in the focusing potential profile. In Fig. 3 the linewidths of all three traces appear comparable, whereas trace (c) shows slightly reduced contrast from traces (a) and (b).

For a more quantitative appraisal of the linewidth and contrast, we performed an average over the $y$ direction for each image and subsequently subtracted a constant 1-nm background to account for the rms fluctuations in the silicon substrate. The results of these calculations are represented as the solid curves in Fig. 4. The linewidths of all three averages are found to be comparable to within the error determined by the sodium grain size. The asymmetry seen in the averages is attributed to a STM tip artifact. The FWHM linewidths inferred from these averages are shown in Fig. 4(a) as 39 nm, Fig. 4(b) as 36 nm, and 4(c) as 40 nm, with contrasts of 10, 17, and 6, respectively.

In Fig. 4 the simulations are compared with averaged line profiles. The height of the simulations has been normalized to correspond to the experimental data. The simulations follow similar trends to those observed in the experimental data: From the simulations we estimate the FWHM linewidths in Figs. 4(a), 4(b), and 4(c) to be 35, 29, and 36 nm and the contrast to be 12, 11, and 8, respectively.

We infer from our experimental results and from Fig. 1 that the profile in which $z_f = +\sigma$ can provide the same resolution as the profile with $z_f = 0$, at 5 times lower input power, provided that $\sigma$ is reduced by a factor of 2. This power reduction could be especially advantageous at large SW detunings, at which the
SW potential is more harmonic and the contrast is superior and the effects of spontaneous emission are reduced. At large detunings the power must be increased to satisfy the timing condition. The factor-of-2 reduction in $\sigma$ that we need to achieve comparable linewidth with this intensity profile causes throughput to decrease dramatically, however, as the confocal parameter is reduced by a factor of 4. Contrarily, the reduction in linewidth seen in the simulations when $z_f = -\sigma/2$ means that resolution can be improved without the reduction in throughput that occurs when $\sigma$ is reduced to improve linewidth. This is achieved, however, with an increase in power of a factor of 5.

In summary, we have found that by manipulating the intensity profile of a SW atom-optical lens we can obtain similar resolution under different experimental conditions. Focusing with the sample placed at $z_f = 0$ provides the best compromise in resolution, contrast, laser power, and throughput. We have also found that by focusing at different positions within the Gaussian SW, we can optimize an atom-optical system for power or throughput without reductions in resolution.

References


4. We define throughput as the time required for making a pattern of a given area and thickness.


13. This saturation intensity is a weighted average for $\delta m_f = 0$ over the $m_f$ sublevels of the $3S_{1/2} \rightarrow 3P_{3/2}$ transition.