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Atomic Deflection Using an Adaptive Microelectromagnet Mirror

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We have deflected a beam of metastable helium atoms using the inhomogeneous magnetic field above a microfabricated electromagnet mirror. The mirror consisted of a single current-carrying wire in a periodic serpentine pattern on a planar sapphire substrate. A time-dependent current (and magnetic field) synchronized with a pulsed thermal atomic beam was used to compensate for the chromaticity of the deflection. The freedom to fabricate a wide variety of geometries and to employ time-dependent fields make microelectromagnets promising new tools for atom manipulation. [S0031-9007(98)06811-2]

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The field of atom optics [1] seeks to develop tools—e.g., lenses, waveguides, beam splitters, and mirrors—to manipulate atoms just as conventional optics manipulate light. Advances in laser cooling [2] and microfabrication techniques have dramatically increased the range of feasible approaches to atomic manipulation. In this Letter, we extend the available atom optical elements to include microelectromagnets [3] consisting of patterns of planar microfabricated current-carrying wires, and we show that these devices can act as adaptive atom optics by employing time-varying currents. Specifically, we report the deflection of metastable helium (He^*) atoms by the inhomogeneous magnetic field above a microelectromagnet mirror consisting of a single current-carrying wire fabricated on a planar substrate in a periodic serpentine pattern. An infinite serpentine array produces a magnetic field whose magnitude decays exponentially with distance away from the array. Atoms with nonzero magnetic moments will experience an exponential potential if the magnetic moment adiabatically follows the local field direction as the atom moves through the field. Vladimirskiĭ first proposed that such a magnetic field configuration could be used as a mirror for neutrons [4]. Opat *et al.* extended the proposal to include realizations of electrostatic mirrors and diffraction gratings for neutral atoms and polar molecules [5].

Several groups have demonstrated mirrors for atoms using static magnetic fields from periodically magnetized materials [6–9] or using evanescent light fields [10]. Both magnetized floppy disks and evanescent light fields have formed curved mirrors suitable for focusing and gravitational trapping of atoms. Recently, Hinds *et al.* have shown how an exponentially decaying magnetic field can form a two-dimensional, surface waveguide for atoms [11].

Microfabricated electromagnet devices [3] extend the usefulness of exponentially decaying fields and offer several advantages over existing magnetic atom optical devices. Specifically, unlike permanent magnets, the strength of a microelectromagnet mirror can be modulated by varying the current flowing through the device. The counterwound geometry has an inherently small inductance ($\leq$100 nH) which results in fast L/R time constants ($\leq$100 ns). One measure of the quality of any mirror is its "flatness"—its ability to reflect a particle beam specularly, without increasing the spread in wave vectors. The ultimate flatness of microelectromagnet mirrors promises to be impressive for three reasons: (1) advanced lithographic techniques can fabricate precisely defined boundaries, (2) Kirchhoff's laws ensure that every segment of the serpentine array carries an identical current, and (3) the fabrication techniques can produce devices with small periods ($\leq 1\ \mu$m) such that the higher harmonics of the field decay rapidly. Many other microelectromagnet configurations are possible; for example, we have fabricated [3] proposed [12] planar microtraps for atoms.

In this paper, we will describe the use of microelectromagnet mirrors to deflect a beam of thermal He* atoms and the use of a time-dependent current to compensate for the chromatic deflection. The details of the fabrication of these devices are published elsewhere [3].

We fabricated devices to create sharp field gradients and high field curvatures [13] by employing wire arrays with small periodicities. Simultaneously, we required large magnetic fields to create deep potentials for atom manipulation. Large field gradients and curvatures provide tight spatial confinement in magnetic traps and reduce the chromatic phase aberrations for magnetic mirrors [5,8]. To maximize the current capacity of our devices, we chose our wire and substrate materials for their electrical and thermal properties, cooled the devices to cryogenic temperatures to reduce electrical resistivity and increase thermal conductivity, and typically operated the devices in a pulsed mode ($\sim$5% duty cycle) to reduce the average heat dissipation. The mirrors were fabricated [3] by photolithography, followed by chemical electrodeposition and subsequent thermal annealing. We have fabricated devices with periodicities ranging from 6 to 200 μm, covering areas from 0.04 to 1.0 cm^2. The cross-sectional profile of the wires can be controlled [3], and this control may be used to optimize the surface field or the mirror flatness.

Figure 1(a) shows a mirror with 48 μm periodicity made of Cu on a sapphire substrate; we have also made mirrors of Au, Ag, and Nb. Because of the critical current limitations, normal metals perform better than superconductors at the small cross-sectional areas desired for atom manipulation: type-II superconducting materials are limited to critical current densities of $\sim 10^7$ A/cm^2, which is lower than the10^8 A/cm^2 we have demonstrated with our smallest gold wires. However, for large area wire arrays ($\geq$1 cm^2) where total heat dissipation is a limiting factor, or for wires of large cross section, superconductors might allow higher current. Mirrors were mounted on a cryogenically cooled copper cold finger, which could be cooled to $\sim$100 K using liquid nitrogen and $\sim$20 K using liquid helium. We have tested a variety of devices and have achieved peak currents of 3 A in a mirror with 48 μm periodicity and 20-μm-wide wires, producing surface field strengths of $\sim$0.1 T. Additionally, we have demonstrated 0.3 T surface fields in continuous operation of sparsely patterned 3-μm-wide Au wires [3].

Although inhomogeneous magnetic fields similar to ours have been used as mirrors to reflect cold atoms, we used the deflection of fast atoms to demonstrate the operation of the "mirror" and to probe the field formed above the device [14]. The device used for these deflection experiments was made of Au, had a large 200 μm period, 92 μm wire width, 12 μm wire height, and covered an area of $\sim$0.5 cm $\times$ 1.0 cm. This device had a calculated inductance of 0.125 μH and a resistance of $\sim$0.5 Ω at 100 K, which results in an L/R time constant of 25 ns. The magnitude of the magnetic field produced above the center of this device is approximately $B = \alpha I \exp(-kz)$, where α is a coefficient with units T/A, I is the current in the wire, $k = 2\pi/\lambda$, λ is the period of the array, and z is the distance from the mirror plane. Because the magnetic fields produced above the center of the wire array do not have a component along the direction of the wires, we can apply an orthogonal bias field along this direction. By measuring the reduction in atomic deflection as a function of this independent field, we determined [15] that α was 5.3 $\pm$ 0.9 mT/A for the 200 μm period mirror. This field strength agrees with simple numerical Biot-Savart calculations.

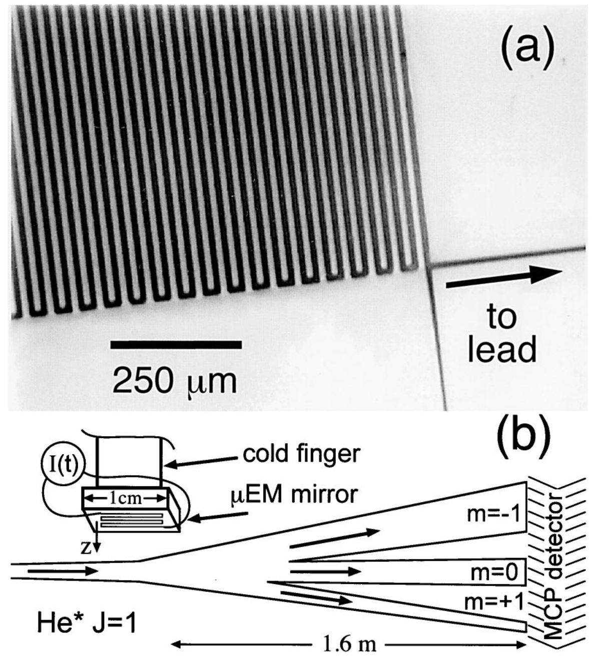

FIG. 1. (a) Photograph of an array of current-carrying wires fabricated for atomic deflection. (b) Schematic representation of the deflection experiment performed in the impulse regime. A fast beam of unpolarized He* ($J = 1$, $m_J = 0, \pm 1$) was passed parallel to the mirror. The position and angle of the mirror were controlled precisely. The spatial distribution of the atoms was measured 1.6 m from the atom-mirror interaction. The repelled (attracted) beam is narrower (wider) because of the lensing effect of the exponential potential.

In our deflection experiments [Fig. 1(b)], a collimated (0.1 mrad) thermal beam of He* atoms in the $2S_1$ state ($J = 1$) passed the mirror at grazing incidence. The atoms traveled parallel to the mirror surface (<0.2 mrad) and parallel to the long direction of the wires to ensure adiabatic following. The mirror was placed 0.2 m from the atomic source, and we detected the spatial distribution of the atoms 1.6 m downstream from the wire array using a microchannel plate detector and a CCD camera. This geometry permitted high resolution detection of small angular deflections (resolution $\sim$0.05 mrad). The atomic beam apparatus has been described in detail previously [16].

An unpolarized distribution of atoms is split by an inhomogeneous magnetic field, just as in the famous Stern-Gerlach experiment [17]. Depending on the magnetic sublevel, different atoms experience either an attractive potential ($m_J = +1$), a repulsive potential ($m_J = -1$), or a flat potential ($m_J = 0$). At the mirror, the spatial extent of our atomic beam in the direction of decaying field strength was $\sim 15\ \mu$m; this spread is smaller than the decay length ($32\ \mu$m) of the exponential field, which was a primary reason for using a large mirror periodicity in this experimental demonstration.

We first describe deflection experiments in which the current of the device was held constant during the interaction of atoms with the field. The deflection was studied as a function of the atom-mirror separation and of the magnitude of the current flowing through the mirror. This interaction can be described as an impulse when the atoms move significantly less than one exponential decay length while interacting with the mirror potential; this criteria can be expressed as $\theta_{\mathrm{def}} kd \ll 1$, where θ_{def} is the angular deflection and d is the length of the mirror. All the experiments described were performed within the impulse regime. Figure 2(a) shows experimental data and corresponding calculations for the deflection of the atomic beam at mirror currents of 0.55, 1.04, and 1.6 A at a fixed beam-mirror separation of $58 \pm 3\ \mu$m. These calculations assume that the atom's magnetic moment adiabatically follows the local field direction, and that the atom experiences a simple exponentially varying field strength [18] as a function of its distance from the mirror. The atom-mirror separation was used as a fit parameter; the fitted value was consistent with experimentally measured clipping of the atomic beam by the mirror. Similar agreement between experiment and theory was obtained at several currents and at other atom-mirror separations.

Figure 2(b) shows experimental profiles of atoms hitting the detector for a variety of atom-mirror separations at a constant mirror current of 1.38 A. For visual clarity, we have not included calculated profiles; however, the peak positions match the calculated peak positions within 10% for all the profiles exhibiting clear peaks [3].

While the gradient of the field above the array deflects the atoms, the curvature of the field acts as a lens. This lens focuses the reflected atoms and defocuses the attracted atoms, such that the reflected peaks are taller and narrower than the attracted peaks. In the impulse regime, the focal length of the effective lens is given by $f = (k\theta_{\mathrm{def}})^{-1}$. Atoms with a velocity of 1800 m/s that are deflected away from the wire array by 0.3 mrad will be focused 0.24 m beyond the interaction, while atoms attracted towards the mirror by 0.3 mrad will appear to originate from a virtual point source 0.06 m behind the mirror. The asymmetry in the reflected and attracted peaks in our deflection data is caused by this focusing effect, but its magnitude is limited by two effects:

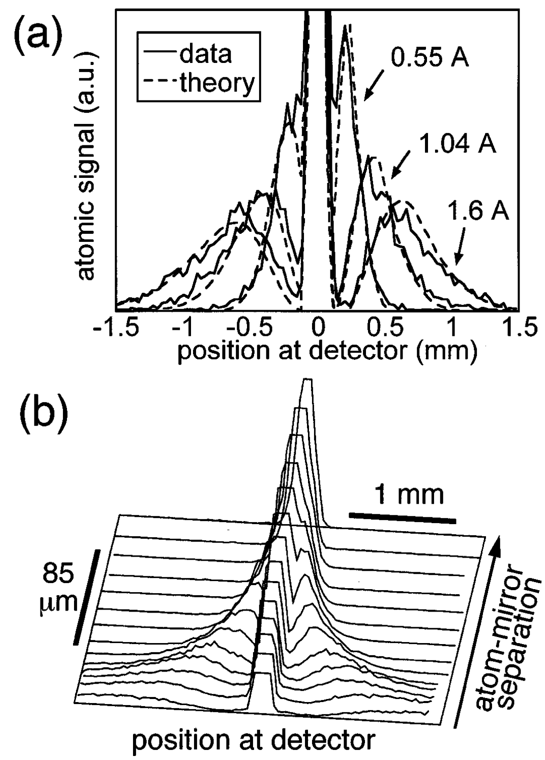

FIG. 2. (a) The experimental (solid lines) and calculated (dashed lines) atomic distributions are shown for mirror currents of 0.55, 1.04, and 1.6 A, with a fixed atom-mirror separation of $58 \pm 3\ \mu$m. (b) Experimental atomic deflection profiles are plotted as a function of atom-mirror separation. The area of the clipped center peak ($m_J = 0$) is comparable to the area of the deflected peaks ($m_J = \pm 1$).

(1) because the potential decays exponentially, the deflection and the focal length are directly coupled, and in our experiment the deflections with observable peak splittings focus well before the detector, and (2) since the atomic beam has a spread in longitudinal velocities, the lens suffers from severe chromatic aberrations.

We now describe the use of a time-dependent current to compensate for the chromatic broadening of the deflected peaks. A large fraction of the width of the deflected peaks in Figs. 2(a) and 2(b) is due to the spread in the longitudinal atomic velocities in our beam. The slower (faster) atoms interact with the potential for a longer (shorter) time, and thus receive a larger (smaller) momentum kick. In the impulse regime, this angular deflection scales as $\theta_{\mathrm{def}} \propto v^{-2}$.

Figure 3(a) shows the timing sequence used in our velocity-compensation experiments. The source was turned on for 1.0 ms, the current was applied with either a flat or ramped profile, and the atoms were detected during a 0.5 ms shutter of our CCD camera. The detected atoms included slower atoms which passed the mirror first and faster atoms which passed later. The instantaneous spread in velocity relative to the total change in mean velocity over the course of the pulse determines the

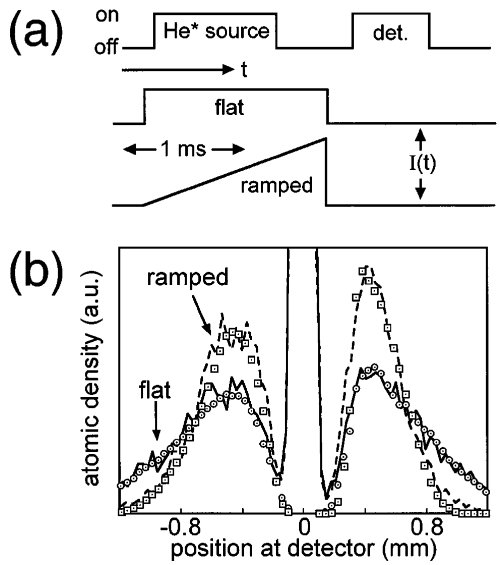

FIG. 3. (a) The atomic source, the device current, and the detector are gated in time for the velocity-compensated deflection. The device current $I(t)$ was either flat (2nd curve) or ramped (3rd curve). (b) Experimental data (flat: solid line; ramped: dashed line) and theoretical calculation (flat: circles; ramped: squares) for the narrowing due to the ramped current are shown. The deflection at constant current was produced with a mirror current of 0.86 A and an atom-mirror separation of 43 ± 3 μm. At the same atom-mirror separation, a current ramped at 1.17 A/ms was used to compensate for the chromaticity of the deflection.

degree to which we can compensate for the chromaticity of the atomic deflection.

Figure 3(b) shows the experimental atomic deflection profiles (solid and dashed lines) and corresponding theoretical calculations (circles, squares) for both flat and ramped current profiles. The experimental data were obtained at an atom-mirror separation of 43 ± 3 μm. A current of 0.86 A was used for the constant current deflection and a linear ramp of 1.17 A/ms was used for the compensating current deflection. We chose a linear ramp on the field magnitude because a properly timed ramp almost perfectly matches the v^2 chromaticity for our timing sequence. Both the starting time and the slope of the ramped pulse were adjusted to optimize the resulting profile for peak separations similar to those obtained with constant current. The starting time was also varied in the calculations to match the experimental data and was found to be consistent with the measured value. The observed spatial narrowing and enhanced peak height of the deflected profile agree with the theoretical predictions. In a velocity-compensated deflection, the focusing-induced asymmetry can be seen more clearly because the chromatic broadening has been reduced relative to the focusing effect. Including a feedback mechanism to adjust dynamically the current profile for optimum velocity compensation would make this a truly adaptive atom optic.

In these velocity-compensation experiments the magnetic field is not changing fast enough to do observable work on individual atoms; rather the narrowing results from atoms experiencing a different quasistatic potential depending on when they interact with the magnetic field. Nonetheless, such a time-dependent potential could be used as a Maxwell demon to accelerate or decelerate cold atoms depending on their arrival time.

To summarize, we have (1) fabricated an atomic mirror from a serpentine planar array of current carrying wires, (2) demonstrated the grazing-incidence deflection of a fast helium beam at a variety of currents and atom-mirror separations, and (3) compensated for the velocity dependence of the atomic deflection angle by employing the ability of electromagnet atom optics to create time-varying potentials. This work begins the experimental development of adaptive atom optical elements which exploit the techniques of advanced microfabrication and cryogenics; these devices can create time-dependent magnetic fields and form mirrors, diffraction gratings, waveguides, and traps.

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[13] The magnetic field strengths, gradients, and curvatures of an arbitrary wire array typically scale as I/d, I/d^2, and I/d^3, respectively, where I is the current and d is the characteristic size. If Ohmic heating limits the current as $I \propto d$, then miniaturization maintains the field strength, increases the gradients as $1/d$, and increases the curvatures as $1/d^2$.

[14] We have operated this mirror with currents up to 5 A; such currents produce a magnetic field sufficient to reflect normally incident He* atoms with a velocity of 12 m/s.

[15] The ratio of the gradients of the field magnitude with and without an orthogonal homogeneous bias field is $(d|B_{\text{bias}}|/dz)/(d|B_{\text{no-bias}}|/dz) = \sqrt{B_y^2 + B_z^2}/\sqrt{B_y^2 + B_z^2 + B_{\text{bias}}^2}$, where B_y and B_z are the fields due to the serpentine wire array.

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