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Reflection of cold atoms from an array of current-carrying wires

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Abstract. We report the realization of a new type of magnetostatic mirror for slowly moving atoms which comprises a planar array of parallel wires alternately carrying electric current in opposite directions. One of the features of this atomic mirror is that the magnetic field may be readily varied, switched or modulated by altering the current in the wires. Reflection signals close to 100% at a pulsed current of 3 A are demonstrated for a beam of free-falling laser-cooled cesium atoms at normal incidence. The current dependence of the reflection signals exhibits structure which is associated with the sequential onset of reflection of cesium $6^2S_{1/2}$, $F = 4$ atoms in the $m = +4$, $+3$, $+2$ and $+1$ magnetic states. Measurements of the spatial distribution of the reflected atoms indicate the reflection is predominantly specular at currents of 3 A.

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1 Introduction

There is currently much interest in developing new and improved atomic mirrors for reflecting beams of slowly moving atoms for atom optics and atom interferometry [1]. The most commonly used atomic mirrors are presently evanescent light-wave mirrors [2–5], which are based on the interaction of the induced electric dipole moment of an atom with a non-uniform light field. An alternative approach exploits the interaction of the permanent magnetic dipole moment of an atom with a spatially varying magnetic field [6]. A periodic array of elements of alternating magnetic polarity generates a magnetic field whose magnitude decreases approximately exponentially with distance above the array. When atoms move adiabatically towards the array they experience a gradient force, which is repulsive for atoms in positive magnetic states ($mg_F > 0$). The array can thus behave as an atomic mirror. Such magnetostatic mirrors have the advantage that they are static, permanent and robust; they do not involve light fields thus avoiding complications associated with spontaneous emission, fluctuating phase shifts and stray near-resonant light; and they can have large reflecting potential and large reflecting area. Magnetostatic atomic mirrors have to date been realized by writing sinusoidal signals on magnetic audio-tape [7], by constructing an assembly of permanent rare-earth magnets of alternating polarity [8,9], and by writing signals on a magnetic floppy disk [10]. More recently, preliminary magnetic mirrors with periodicities on the scale of microns have been produced by fabricating magnetic structures comprising arrays of parallel grooves [11,12].

Another type of magnetostatic mirror has been proposed [6] which is based on the magnetic field produced above an array of parallel wires alternately carrying electric current in opposite directions (see, *e.g.*, Fig. 1). A precursor of such an array, *i.e.*, a *single* current-carrying wire, has recently been used to demonstrate the transverse Stern-Gerlach deflection of a beam of free-falling cold cesium atoms [13]. Current-carrying magnetic mirrors have a number of potential advantages over mirrors based on permanent magnets. The magnetic field may be readily varied, switched or modulated by altering the current in the wires; each element in the series array carries the same current and hence produces the same magnetic flux; and it should be possible to fabricate very flat magnetic mirrors on optically flat substrates (such as silicon, CVD diamond or sapphire). In this paper we report the realization of such a current-carrying mirror and demonstrate the reflection of a beam of laser-cooled cesium atoms normally incident on it. Preliminary accounts of the design and fabrication of the mirror have been reported previously [12,14]. Very recently an array of current-carrying wires similar to that described here has been used to deflect a thermal beam of metastable helium atoms at grazing incidence [15].

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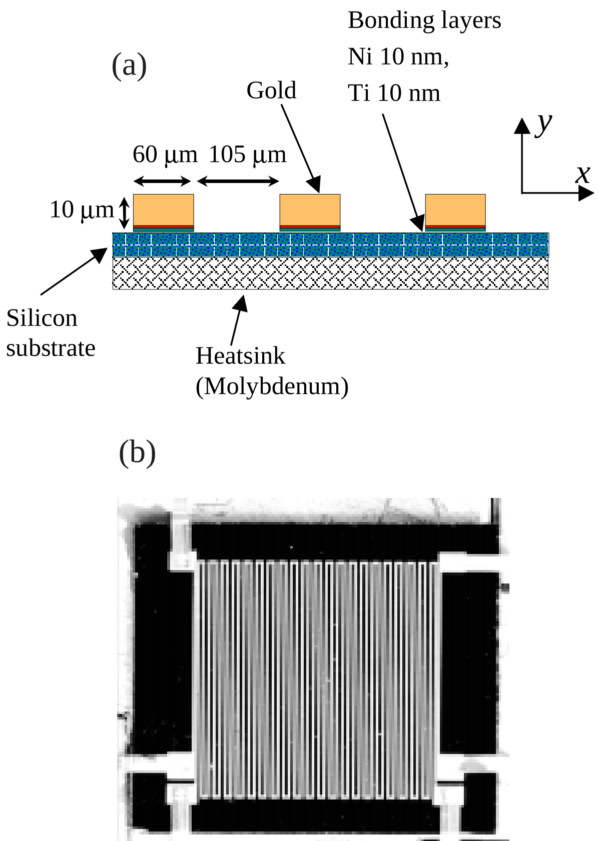

Fig. 1. (a) Schematic diagram of the cross-section of part of the current-carrying wire mirror. (b) Photograph of the current-carrying wire mirror, consisting of an array of 42 parallel gold wires and two compensating wires on the ends.

2 Physical principles

We consider the inhomogeneous magnetic field produced above an array of *thin* wires alternately carrying electric currents of equal magnitude I in opposite directions (see, *e.g.*, Fig. 1). For an *infinite* array of wires, the components of the magnetic field above the array may be described by [6]

$$B_x(x,y) - iB_y(x,y) = -i\frac{\mu_0 I}{a}\,\frac{1}{\sin\big(k(x+iy)\big)} \qquad (1)$$

where y is the distance from the array normal to the surface, x is the distance in the plane of the array perpendicular to the direction of the wires, $k = 2\pi/a$, and a is the periodicity of the array given by twice the spacing of the centroids of the wires. For distances above the surface $y > a/2\pi$, the magnitude of the magnetic field may be expressed as [16]

$$B(x,y) = \frac{2\mu_0 I}{a}e^{-ky}(1 + e^{-2ky}\cos 2kx + \cdots). \qquad (2)$$

Thus when an atom in a positive magnetic state ($mg_F > 0$) is moving adiabatically towards the surface of the array, it experiences a gradient force $\mathbf{F} = -mg_F\mu_B\boldsymbol{\nabla}B(x,y)$ that repels it from the surface, and if the potential barrier produced by the magnetic field is sufficiently high the atom will be reflected by the array. The first term in equation (2), which decays exponentially with decay length $a/2\pi$, is dependent only on the coordinate y and is responsible for specular reflection (a mirror term). The second term exhibits a periodic dependence on the transverse coordinate x and produces a corrugation in the magnetic field magnitude, which can give rise to diffuse reflection. However this corrugation term decays much faster with y than the first (mirror) term. For atoms of mass M dropped from height h the relative amplitude of the corrugation term in equation (2) is given by $C \approx [Mgh/(mg_F\mu_B B_0)]^2$, where $B_0 = 2\mu_0 I/a$ is the characteristic pre-exponential magnetic field in equation (2). For $I = 3$ A and $a = 330$ μm, B_0 is about 230 G. For sufficiently strong magnetic fields such that the atom is reflected at distances $y \gg a/4\pi$ the second (corrugation) term may be neglected, and reflection should be predominantly specular.

For an array with a *finite* number of *thin* wires, the expression for the magnetic field components becomes [16]

$$B_x(x,y) - iB_y(x,y) = -i\frac{\mu_0 I}{a}\Big[\frac{1}{\sin\big(k(x+iy)\big)} + \frac{a}{4\pi(x+iy+w+a/4)} - \frac{a}{4\pi(x+iy-w-a/4)}\Big] \qquad (3)$$

where $2w$ is the width of the array in the x direction. Equation (3) shows that the magnetic field distribution may approximate the infinite case if two wires carrying half the current are added at $x = \pm(w + a/4)$, *i.e.*, at the ends of the array at half the normal spacing.

Model calculations of the magnetic field profiles for a finite array of width $w = 7$ mm consisting of 42 parallel wires of *finite width* 60 μm and periodicity $a = 330$ μm were performed by numerically integrating over the width of the wires. Curve 1 of Figure 2 shows the magnetic field at height $y = 80$ μm for a current of 3 A and no compensating wires. Under these conditions the magnetic field in the central region of the array is about 45 G, which is sufficient to reflect cesium $F = 4$, $m = +4$ atoms dropped from a height of 19 mm. Curve 2 shows that when compensating wires are added the oscillations at the periodicity $a = 330$ μm are almost completely suppressed, confirming that these oscillations originate from "end effects" associated with the finite number of wires. The residual corrugations, at half the periodicity of the array, originate from the corrugation term in equation (2).

3 Experimental

3.1 The current-carrying mirror

The magnetic mirror consists of an array of 42 parallel gold wires, each 60 μm wide, 8 mm long and 10 μm thick, prepared on a highly polished silicon substrate which is bonded to a molybdenum heat sink (Fig. 1). The periodicity of the array is $a = 330$ μm, the active area

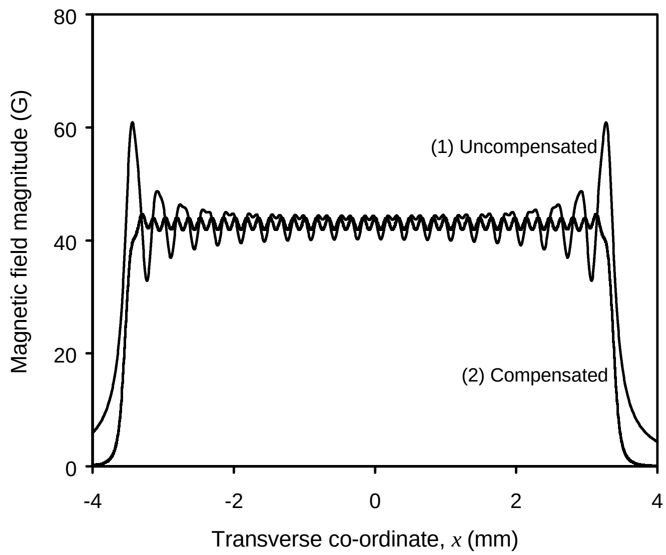

Fig. 2. Calculated magnitude of the magnetic field at height $y = 80\ \mu$m above an array of 42 parallel wires, each 60 μm wide and 8 mm long, with periodicity $a = 330\ \mu$m, and carrying a current of 3 A. (1) No compensating wires; (2) with compensating wires carrying half the current and located at the ends of the array at half the normal spacing.

7 mm × 8 mm, the low-current resistance 16 Ω and the inductance 100 nH. Silicon was chosen as the substrate because of its well-known characteristics from experience with fabrication of microelectronics and its reasonably high thermal conductivity. However because of its semiconducting properties silicon is limited to relatively low operating temperatures.

The mirror was fabricated in the following way:

(i) 10 nm-thick bonding layers of titanium and nickel were vacuum-evaporated onto a polished high-purity silicon wafer, followed by a 100 nm-thick seed layer of gold.
(ii) Photoresist was spun onto the gold surface.
(iii) Photolithographic techniques involving UV light transmitted through a computer-generated mask of the required mirror pattern were used to expose the photoresist.
(iv) The photoresist was processed and the exposed region removed.
(v) A further layer of gold was electroplated between the walls of the remaining photoresist onto the gold seed layer to a thickness of about 10 μm.
(vi) The remaining photoresist was removed and the residual seed layer of gold chemically etched away to form the final gold structure.
(vii) The surface of the mirror was coated with a 100 nm protective layer of silica.

The mirror is activated by applying current pulses of duration typically 10–12 ms at a repetition rate of about one every four seconds synchronous with the trapping/cooling/release cycle described below. Peak currents up to 3.8 A were used, corresponding to a current density of 6×10^5 A cm^{-2} and an average power dissipation of 0.6 W. For 3 A current pulses, the increase in temperature of the wires during each pulse is estimated from the change in resistance of the gold to be less than 10 °C. At these temperatures current leakage due to the electrical conductivity of the pure silicon substrate is still negligibly small. The compensating wires at the ends of the array were not activated in the measurements reported here.

3.2 The cold atom source

The laser cooling set-up is similar to that described previously [8]. Cesium atoms are loaded from a vapor at a background pressure of about 3×10^{-9} torr into a standard magneto-optical trap (MOT) using three pairs of counter-propagating σ^+–σ^- laser beams tuned about 10 MHz to the red of the $6^2S_{1/2}(F = 4) \rightarrow 6^2P_{3/2}(F' = 5)$ laser cooling transition at 852 nm. The laser beams are derived from a 150 mW single-frequency diode laser which is injection-locked to an extended-cavity master diode laser. The master laser is locked to the center of the saturated-absorption cross-over resonance $F = 4 \rightarrow F' = 4, 5$, which is 126 MHz below the cooling transition. A (110 ± 25) MHz acousto-optic modulator (AOM) in double-pass configuration between the master and the slave lasers allows variable detuning from the cooling transition of the first order output of a second AOM, which is positioned in the output of the slave laser for switching and intensity control of the laser cooling beams. The laser-cooling beams are combined with a repumping beam tuned to the $F = 3 \rightarrow F' = 4$ transition and then expanded to 20 mm diameter with about 5 mW in each beam.

After loading the trap, typically with about 10^7 atoms in a cloud of diameter about 2 mm, the atoms are cooled in optical molasses (at a detuning 50 MHz and at about half the laser trapping power) for 20 ms. The molasses is then switched off, releasing the cold atoms to free-fall under gravity. Time-of-flight (TOF) absorption measurements, using a probe beam locked to the $F = 4 \rightarrow F' = 5$ transition and positioned 12–14 mm beneath the trap, yield a molasses temperature of about 10 μK, corresponding to an rms velocity spread of 3.5 cm s^{-1}. After release from the molasses the free-falling atoms pass through two counterpropagating beams of σ^+-polarized $F = 4 \rightarrow F' = 4$ light to optically pump them towards the $m = +4$ state. The optical pumping beams are combined with a $F = 3 \rightarrow F' = 4$ repumping beam to reduce losses due to spontaneous decay into the $F = 3$ ground state. A weak magnetic field of about 0.5 G is applied in the direction of the pumping beam to provide a quantization field and to ensure the optically pumped atoms remain in the same magnetic quantum state.

3.3 Atomic reflection measurements

The mirror is positioned 18–20 mm beneath the trap and is activated with a current pulse to coincide with the arrival of the free-falling atoms. The incident and reflected

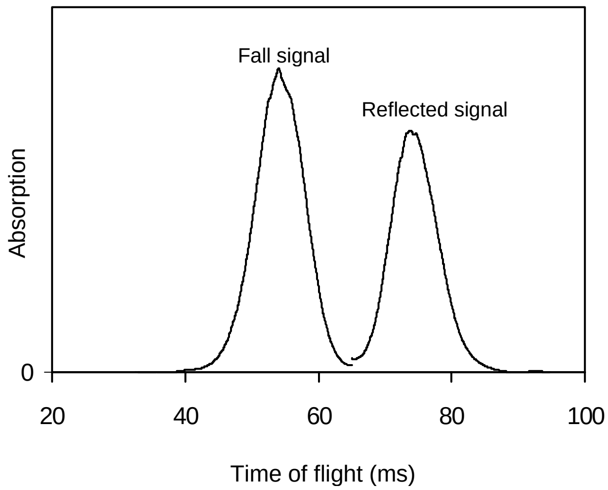

Fig. 3. Time-of-flight absorption signals for the falling and reflected σ^+-pumped cesium $F = 4$ atoms dropped from a height $h = 20$ mm above the mirror. The wire mirror was activated with a current pulse of 3 A and 12 ms duration to coincide with the arrival of the falling atoms. The reflected signal was recorded by turning on the σ^+-polarized probe beam just prior to arrival of the reflected atoms.

atoms are detected by measuring the TOF absorption of a weak ($\sim 0.3\ \mu\text{W cm}^{-2}$) σ^+-polarized probe beam tuned to the closed $F = 4 \to F' = 5$ transition. A thin elliptically shaped probe beam (1 mm thick, 20 mm wide) is positioned about 6 mm above the mirror along the long direction of the wires. When measuring reflectivities, the probe beam is turned on just prior to arrival of the reflected atoms, to ensure the reflected atoms have interacted only with the optical pumping beam prior to detection. Mechanical shutters are used to completely block out any stray near-resonant light.

4 Results

4.1 Reflection measurements

Figure 3 shows the TOF absorption signal recorded for σ^+-pumped cesium $F = 4$ atoms dropped from a height of 20 mm above the mirror when the mirror is activated with a 3 A current pulse of 12 ms duration. The mean velocity of the atoms incident on the mirror is 62 cm s^{-1}. The first TOF peak, near 54 ms, corresponds to absorption by atoms falling through the probe beam after release from the optical molasses. The second peak, near 74 ms, corresponds to absorption by atoms which have been reflected from the mirror. To verify that the second peak corresponds to atoms reflected by the magnetic field above the array, additional measurements were taken with a σ^--polarized optical pumping beam, and also with the timing of the current pulse mismatched with the arrival of the atoms at the mirror. In each of these cases the reflected peak was negligibly small ($\ll 1\%$ of the fall signal).

The ratio of reflected to incident absorption signals taken from the measured areas under the TOF curves is

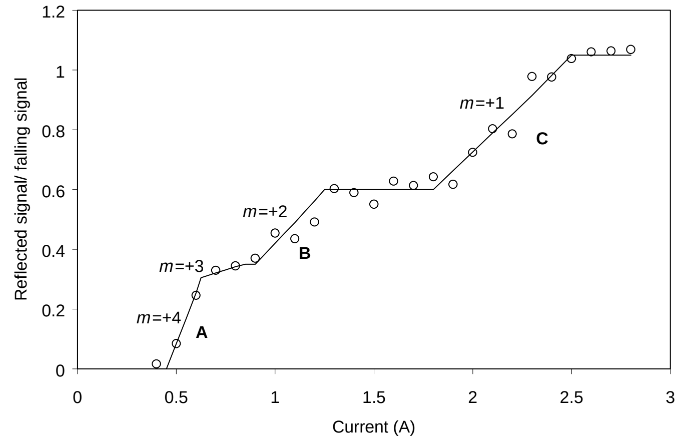

Fig. 4. Current dependence of the ratio of the absorption signals for the reflected and incident atoms dropped from a height $h = 18.5$ mm above the mirror. No dedicated optical pumping beam was employed. The solid curve represents a fit to the data based on a simple model, as described in the text.

$(77 \pm 2)\%$. From the measured velocity spread of the atoms ($\sim 3.5\ \text{cm s}^{-1}$) and from the observed spatial distribution of the falling atoms (Sect. 4.3), we estimate that about 17% of the falling atoms actually miss the mirror. Any misalignment or tilt of the mirror will result in a larger loss of atoms. A small loss may also occur for those atoms which strike the edges of the mirror where corrugations are largest (Fig. 2). After allowing for the loss of atoms missing the mirror and a further estimated loss of 5% for those atoms that arrive outside the 12 ms duration of the current pulse, we find the corrected reflectivity at a current of 3 A to be $(98 \pm 5)\%$.

Measurements taken in the absence of an optical pumping beam (but still with the probe beam turned on just prior to arrival of the reflected atoms) yield a corrected reflectivity of only 25%, which is consistent with earlier observations that the atoms leave the molasses predominantly in low $|m|$ states [13]. We note that, unlike the situation with our permanent rare-earth magnetic mirror [8], the magnetic fields available from this current-carrying mirror (about 200 G at 3 A) are too small to allow reflection of $m \leq 0$ atoms by the repulsive gradient force associated with the quadratic Zeeman effect.

4.2 Current dependence

Figure 4 shows the measured ratio of reflected to incident absorption signals as a function of current through the wire array for atoms dropped from a height of 18.5 mm. In this experiment no dedicated optical pumping beam was employed, though some optical pumping would have occurred as the atoms fell through the σ^+-polarized $F = 4 \to F' = 5$ probe beam which was left constantly on. The observation of apparent reflectivities greater than 100% in this experiment is attributed to optical pumping by the probe beam of atoms in low m states to more strongly absorbing high positive m states.

The observed threshold current for reflection of cesium atoms dropped from a height of 18.5 mm is 0.45 A (Fig. 4), which is close to the calculated threshold current for reflection of cesium atoms in the $m = +4$ state. The threshold currents for reflection of atoms in other magnetic states are thus expected to be 0.6 A ($m = +3$), 0.9 A ($m = +2$) and 1.8 A ($m = +1$) (the threshold current for atoms in the $m = 0$ state is estimated to be 5.4 A). The observed current dependence exhibits three regions of steeply rising reflectivity designated in Figure 4 by A, B and C. The observed thresholds for B and C closely match the expected threshold currents for the $m = +2$ and $m = +1$ states. The threshold for the $m = +3$ state (0.6 A) is close to that for $m = +4$ (0.45 A) and is not expected to be well resolved in this experiment. Thus we identify the regions A, B and C as representing the sequential onset of reflection of atoms in the $m = +4$ (and +3), +2 and +1 states, respectively. This identification is further supported by the observed current ranges of the three regions A, B and C, which are approximately proportional to $1/m$. The threshold currents for $m = +4$ atoms determined for a range of different drop heights are found to increase linearly with drop height, in accordance with what is expected in the linear Zeeman effect regime.

The solid curve in Figure 4 represents a fit to the data based on a simple model in which the individual contributions of atoms in the magnetic states $m = +4$, +3, +2 and +1 are summed, with the populations treated as free parameters. In this model, we assume for each state a simple linear increase in reflectivity, over a current range from threshold up to a saturation value, as the regions (in the xz plane) where the magnetic field exceeds threshold grow in size and coalesce. The current range for atoms in the $m = +4$ state was determined from a fit to the data, and the current ranges for atoms in the other states were scaled in accordance with their magnetic quantum numbers. The relative populations of the states given by the fit are about 30% ($m = +4$), 5% ($m = +3$), 25% ($m = +2$) and 40% ($m = +1$). Such a distribution of populations is not unreasonable if many of the falling atoms are not optically pumped by the weak ($\sim$ 0.3 μW cm^{-2}) probe beam, but instead remain in the low $|m|$ states in which they leave the molasses [14].

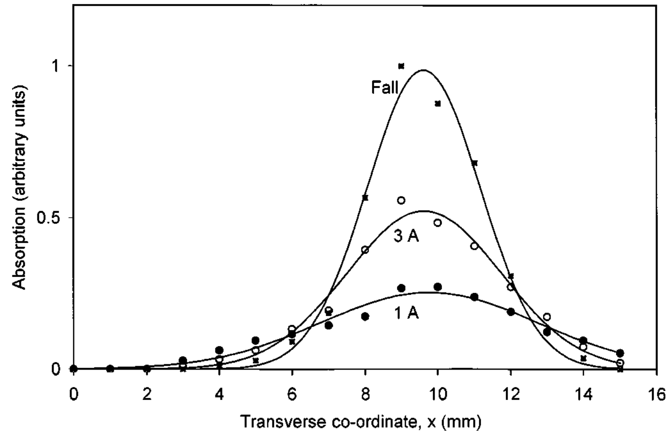

Fig. 5. Spatial distributions of the incident atoms and reflected atoms for pulsed currents of 3 A and 1 A. The solid curves represent Gaussian fits to the data. Drop height = 19 mm.

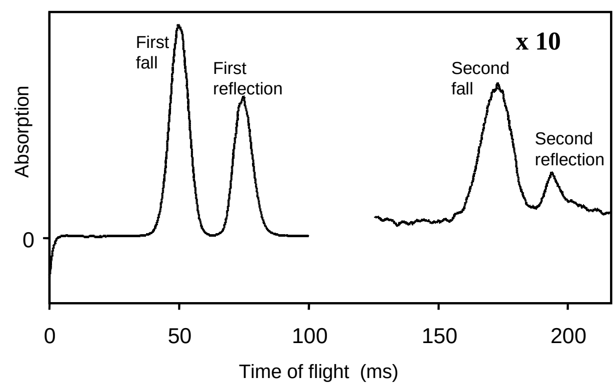

Fig. 6. Time-of-flight absorption signals showing the first and second reflection signals of cesium atoms bouncing on the current-carrying wire mirror.

4.3 Spatial distribution

Measurements of the spatial distributions of the incident and reflected cesium atoms are shown in Figure 5 for pulsed currents of 3 A and 1 A. The data were obtained from TOF absorption signals taken by stepping a 1 mm-diameter probe beam sequentially across the mirror in the (transverse) x direction at 6 mm above the mirror. The σ^+-polarized optical pumping beams were used in these experiments.

At the high current of 3 A, the spatial distribution of the reflected atoms is found to be close to that of a specularly reflected atomic beam allowing for ballistic expansion associated with the initial velocity spread of the atoms. The additional rms velocity spread introduced by diffuse reflection by the mirror is estimated from the spatial profiles to be about 2.7 cm s^{-1} corresponding to an rms angular spread of about 45 mrad (equivalent to about seven photon recoils). At the low current of 1 A, the spatial distribution of the atoms is significantly broader (equivalent to about 40 photon recoils), which is consistent with the atoms being reflected from much closer to the surface of the mirror where the corrugations and hence diffuse reflection are larger.

4.4 Additional time-of-flight investigations

Figure 6 shows the TOF signal taken when the mirror is activated with a second current pulse to coincide with the arrival of atoms which have fallen back to the mirror after the first reflection. The positions of the second fall (173 ms) and second reflection peak (194 ms) correspond approximately to the expected arrival times of the atoms. The second reflection signal is rather small (about 1.5% of the first fall), largely due to the small fraction of atoms that strike the mirror after 183 ms of ballistic expansion.

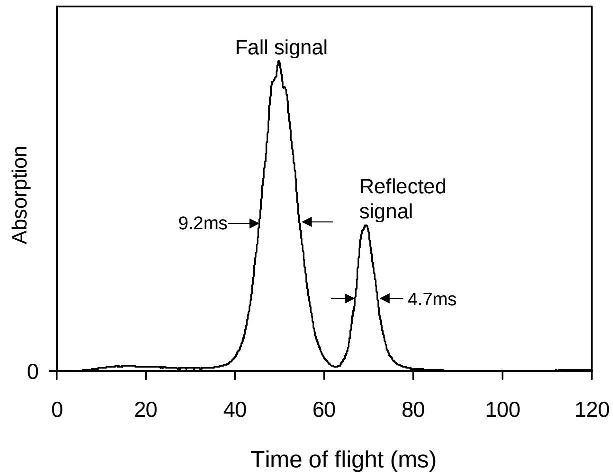

Fig. 7. Time-of-flight absorption signal showing the narrowing of the reflected signal when the duration of the current pulse is reduced to 4 ms.

Other losses could result from some of the atoms not intersecting the probe beam after ballistic expansion and from collisional losses in the beam [8].

When the duration of the current pulse is reduced from 10 ms to 4 ms, the width of the TOF reflection signal is found to decrease by a factor of about two (Fig. 7), due to the fact that only those atoms in the velocity distribution that arrive within the 4 ms interval are reflected. The observed narrowing of the TOF signal due to such "velocity filtering" corresponds to a factor of about four reduction in the 1D temperature in the vertical direction. The amount of observed narrowing is limited by the finite size of the molasses and the thickness of the probe beam. Similar velocity filtering effects have been observed with pulsed-light evanescent-wave mirrors [17].

5 Summary and discussion

We have demonstrated the operation of a new type of magnetostatic mirror for slowly moving atoms which is based on a planar array of current-carrying wires. Reflectivities close to 100% have been found at pulsed currents of 3 A for an optically pumped beam of free-falling laser-cooled cesium atoms at normal incidence. A second reflection signal, from atoms that have fallen back to the mirror after the first reflection, has also been observed. Velocity filtering of the atoms has been observed when the duration of the current pulse was reduced to less than the spread in arrival times of the atoms. Measurements of the spatial distribution of the reflected atoms indicate that at a current of 3 A the reflection is predominantly specular, and the velocity spread introduced by corrugations in the mirror is estimated to be equivalent to about seven photon recoils. More stringent tests of the specularity are required, for example, by measuring the expansion of a finely collimated cesium beam over extended periods of time after reflection [18].

Current-carrying magnetic mirrors have a number of potential advantages over mirrors based on permanent magnets. The ability to vary the current provides an additional degree of freedom, allowing the magnetic field above the mirror to be varied, switched or modulated. Such a mirror thus offers interesting possibilities such as the use as a velocity filter for slowly moving atoms. Each element in the series array carries the same current and hence produces the same magnetic flux, and the magnetic field above the array can be modelled reliably thereby allowing the mirror to be readily characterized. Substrates, such as silicon, CVD diamond or sapphire, with optical flat quality should allow the fabrication of very flat current-carrying mirrors. Finally, the use of photolithographic techniques will allow the fabrication of complex wire patterns [15,19], such as cylindrical mirrors comprising arrays with variable wire spacings.

The performance of the prototype mirror could be improved substantially in future versions. Model calculations of the profiles of the magnetic field indicate that by activating the compensating wires at the ends of the mirror to reduce end-effects the corrugations could be reduced by a factor of about two. Substantial reductions in the corrugations due to higher-order spatial harmonics will be possible by using higher peak current in the wires to generate higher magnetic fields. For a pulsed current of 3 A and 10 ms duration, the increase in temperature of the wires is estimated to be less than about 10 ℃. Use of a peak current of 8 A, for example, would be expected to raise the temperature by less than 70 ℃ and to reduce the corrugations by a further factor of about seven. At 90 ℃ the silicon substrate would conduct, and it will be necessary to use another substrate such as CVD diamond or sapphire, both of which also have higher thermal conductivities than silicon. The peak current could be further increased by using gold wires with larger cross-section; for example, by increasing the wire thickness from 10 μm to 60 μm to form a square cross-section, it should be possible to raise the current by a further factor of about 2.5. Finally, the use of cryogenic cooling will increase the electrical and thermal conductivity of the gold and also the thermal conductivity in the case of sapphire, and allow substantially higher peak currents [15].

Magnetostatic mirrors, like evanescent light-wave mirrors, are intrinsically dispersive elements, with the distance of approach and the phase shift $\Delta\varphi = -(2ap/h)\cos\theta_0 + \pi/2$ [6] (where θ_0 is the angle of incidence from the normal) being proportional to the momentum p of the atoms and to the periodicity a of the mirror. Current-carrying mirrors with much smaller periodicities are needed in order to produce a "hard" mirror so that atoms with a spread of velocities are reflected over a narrow range of distances and with a small range of phase shifts, and in order to produce coherent mirrors and diffraction gratings for slowly moving atoms. The use of smaller periodicity will in general result in larger ohmic heating. However, for a mirror of giving wire thickness and given area and assuming a wire width that scales as a, the increase in temperature is expected to scale as I^2/a^2, or as B_0^2 (Eq. (1)), which is independent of the periodicity a. We estimate that by maintaining a constant wire thickness it should be possible to reduce the periodicity by at least an order of magnitude. Use of cryogenic cooling has recently allowed the construction and operation of current-carrying gold arrays with periodicities down to about 50 μm, where the operating currents were 3 A (pulsed) and the surface magnetic fields about 1 kG [15].

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