Magnetic whispering-gallery mirror for atoms

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Videotape with a sinusoidal magnetization of 31 μm wavelength is used to reflect Cs atoms with unit reflectivity in a 75 m/s atomic beam. The atoms serve as a probe, allowing us to measure the magnetic field at the surface. A technique is presented for mounting the videotape so that its surface can be curved to a specific shape or made flexible. We show that such a reflector provides high-quality grazing-incidence atom optics and we demonstrate deflections as large as 23° in a whispering-gallery geometry.

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I. INTRODUCTION

Beams of atoms can be manipulated to project well-defined patterns onto a surface or otherwise controlled to make useful instruments. Perhaps the first example of this was the famous Stern-Gerlach experiment [1] in which a beam of atoms was deflected by inhomogeneous dc magnetic fields to probe the atomic spin. This technology was subsequently improved for atomic beam magnetic resonance by the use of multiple magnetic elements [2]. With the advent of laser cooling it became possible to prepare slow and very bright atomic beams [3] and this has led to a recent surge of interest in atom optics [4,5]. For example, atomic beam imaging has been demonstrated using diffraction through a microfabricated Fresnel lens [6] and using deflection in a magnetic hexapole lens [7]. Many of the basic elements of atom optics have also been demonstrated using diffraction or deflection of atoms by laser light [8]. The imaging properties of such elements are generally compromised when the atom beam has a spread of velocities, whereas this chromatic aberration can be largely avoided by the use of reflection optics. The retroreflection of atoms is now well established and can be accomplished using a microscopic pattern of permanent magnetization [9] or a miniature array of current-carrying wires [10]. Very recently, a millimeter-sized thermal cloud of atoms was achromatically imaged using a concave magnetic reflector based on videotape [11]. More details and an overview of magnetic atom optics can be found in a recent review [5].

One attractive feature of atom optics is the short wavelength of the de Broglie waves, ranging from a few hundred nanometers for atoms close to the recoil limit of laser cooling down to tens of picometers for atoms at room temperature. In principle, such short wavelengths promise very high spatial resolution for use in atom lithography and other imaging applications. However, atom optics is severely limited over most of this range by the large energy barriers needed to produce significant deflections. For example, the field in front of a magnetic mirror repels an atom with the potential barrier $-\mu_\zeta B$, where B is the field strength and μ_ζ is the atom's magnetic moment projected onto the field. With a maximum field B_0 of, say, 0.1 T and a magnetic moment of $-\mu_B$ (the Bohr magneton) the energy barrier expressed as a temperature $\mu_B B_0/k_B$ is only 67 mK. For Cs atoms, which are used in this experiment, the corresponding maximum normal velocity is only 2.9 m/s and a beam traveling faster than this can be reflected only if it impinges on the mirror at an angle $\theta \leqslant \theta_{\max}$. For an atomic beam of velocity v, the maximum grazing angle for reflection is given by

$$\sin\theta_{\max} = \sqrt{\frac{\mu_\zeta B_0}{mv^2}}. \tag{1}$$

One is therefore faced with a problem very similar to that of x rays, where the short wavelength offers excellent resolution, but the reflection optics must be at grazing incidence. These considerations motivated us to build a cylindrical magnetic reflector, designed to deflect a Cs beam through a large angle by many grazing reflections, as a first step toward reflective imaging optics for thermal atomic beams.

II. CONSTRUCTION OF THE REFLECTOR

The reflecting field of the mirror was made by recording a sine wave on 12-mm-wide videotape (Ampex 398 Betacam SP). This was done using a standard data storage tape drive to which we added a custom-made recording head (Phi Magnetronics 0604B). The head has a 12 μm pole gap and is long enough to record across the entire width of the tape. Using a 2 kHz signal and a tape speed of 6 cm/s we wrote a pattern of magnetization

$$\mathbf{M} = \mathbf{M}_0 \sin(\mathbf{k}\cdot\mathbf{x})\hat{\mathbf{x}}, \tag{2}$$

where the spatial period is $\lambda \equiv 2\pi/k$ and $\hat{\mathbf{x}}$ is the direction along the length of the tape as shown in Fig. 1. We were able to check the period using a glass slide coated with a thin film of lutetium bismuth iron garnet (Bi:LuIG) [12], which was placed on top of the tape. The polarization of light passing through the film was altered according to the magnetic field

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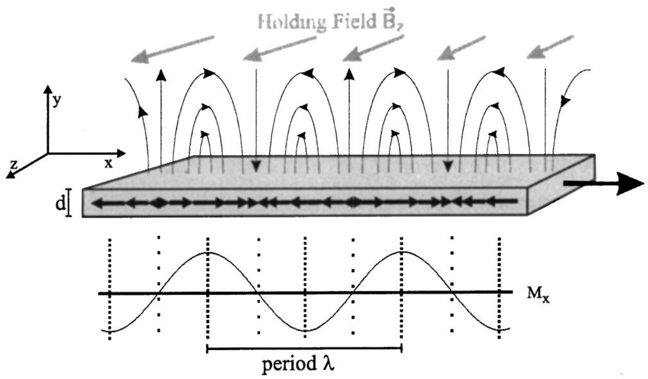

FIG. 1. Schematic of periodically magnetized videotape. The magnetization lies in the *xz* plane.

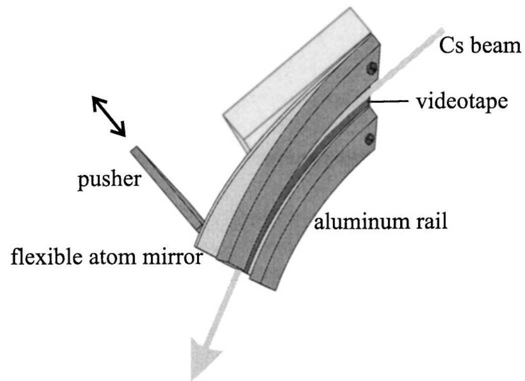

FIG. 3. The sinusoidally recorded tape is glued to a metal strip that can be bent into a curve by pushing on the end as shown. The slow atomic beam can be deflected by multiple bounces through angles as large as 23°.

because of the induced birefringence. Consequently, a polarization-sensitive microscope revealed the magnetic field as a pattern of intensity fringes, shown in Fig. 2. These gave the period as 31 μm.

Assuming that the magnetization is the same throughout the 3.5 μm depth d of the magnetic layer, one can show [5] that the magnitude of the field in front of the tape is

$$B=\frac{1}{2}\mu_0 M_0(1-e^{-kd})e^{-ky}\equiv B_0 e^{-ky}. \quad (3)$$

We note that this is independent of the transverse position (x,z) and therefore the magnetic repulsion between the atom and the mirror is normal to the surface, i.e., along $\hat{\mathbf{y}}$. Since M_0 cannot exceed the remanent magnetization of 180 kA/m, the largest B_0 for this tape is 58 mT. We tried to approach this by choosing our recording parameters (amplitude and frequency of the current in the recording head and tape speed) so that the magnetization of the tape was just saturated while maintaining a variation as close as possible to sinusoidal. Oversaturating the tape results in a square-wave magnetization pattern. We could not measure the field at the surface using standard probes because it varies on a microscopic length scale and standard microscopic analysis methods yield only relative field measurements at present. The experiment reported here, however, allowed us to determine the value of B_0 by atom reflection, as described in the next section.

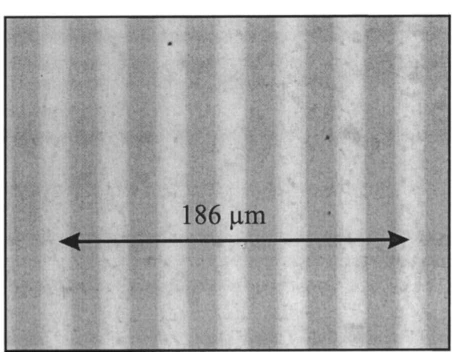

FIG. 2. Photograph of the magnetized videotape taken through a thin film of garnet with a polarization-sensitive microscope. The magnetic sine wave is clearly visible.

To prepare the tape for our experiments we glue it to a strip of commercial 35 mm photographic film using a slow-drying, low-viscosity epoxy (Bylapox 7285). The film is placed emulsion side down on a 3.4-mm-thick sheet of float glass, supported by a flat aluminum baseplate. After applying the glue evenly to the back of the film, we wait 10 min to allow the air bubbles to disperse. The tape is then laid on the glue, taking care not to trap any air bubbles. Further layers of film, glass, and aluminum complete a ''sandwich'' that is tightly clamped for 24 h while the glue dries. In order to avoid dust this is done in a clean laminar flow box. The resulting tape/film combination is durable, smooth, and flexible enough to be curved. The reflector is completed by gluing it to a substrate. For one of our mirrors this is simply a flat glass plate, but we also use a flexible phosphor bronze strip in order to make a cylindrical mirror of variable curvature. Each end of the tape/film is bent around the end of the substrate, rather than being cut. This proved essential for the success of atomic beam experiments, presumably because it allows the atoms impinging at grazing incidence to enter the magnetic field smoothly, rather than passing suddenly through an ill-defined fringe field region.

We checked the physical roughness of the mounted videotape by scanning it under an atomic force microscope. Over a 1 μm square the rms height variation is only 7 nm. We do not expect roughness on this small scale to have a significant effect on the quality of the magnetic field many micrometers above the surface, where atoms are typically reflected. A mounted and curved section of tape was also studied at the University of Erlangen by Dresel, Häusler, and Venzke using the method of coherence radar [13]. This allowed us to look over much larger distances to see if the tape was really being held flat. The measurements showed that unwanted height variations of the tape over lengths of 1 mm are too small to detect and therefore less than 1 μm.

Figure 3 shows the variable mirror assembly. The 4.5-cm-long flexible strip is clamped between a flat aluminum block and a pair of curved aluminum rails, whose outer radius of

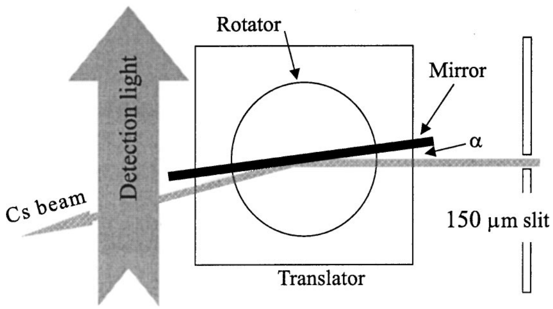

FIG. 4. Experimental arrangement for investigating reflection of atoms.

curvature is 9.6 cm. In this way the curvature of the videotape surface could be smoothly varied by pressing on the back of the strip as indicated in the figure. The largest angle that could be subtended by the curved mirror was 22° because the strip was too stiff to be pushed fully against the rails. Our atom reflector was mounted on a motor-controlled rotation stage, sitting in turn on a translation stage. These provided the necessary mechanical adjustments for bringing the atomic beam onto the mirror at grazing incidence.

III. EXPERIMENTAL TESTS OF THE REFLECTOR

A. Plane mirror

In our first experiment, we studied the reflection of atoms from an 11-cm-long plane mirror, with the experimental arrangement shown in Fig. 4. The horizontal Cs beam, produced by a Zeeman slowing apparatus described elsewhere [3], delivers $6\,^2S_{1/2}$ ground state Cs atoms in the magnetic hyperfine sublevel $(F=4,m_f=4)$. These atoms have magnetic moment $\mu_\zeta=-\mu_B$. The beam velocity is adjustable and is measured by the Doppler effect, using a laser beam propagating at 155° to the atomic beam to induce resonance fluorescence on the transition $6\,^2S(F=4)\rightarrow 6\,^2P(F=5)$. A plot of fluorescence intensity versus laser frequency is readily interpreted to give the velocity distribution of the atoms. In this experiment the central velocity is 75 ± 3 m/s and the full width at half maximum spread is approximately 10 m/s. The physical width of the beam is constrained to 150 μm by a slit located 20 cm upstream from the center of the mirror and the angular spread is limited to 1.1 mrad by a second slit 700 μm wide and 95 cm from the mirror. Atoms incident at grazing angle α are reflected from the tape before passing through a resonant horizontal light beam (2 mW power with a few mm diameter), where they fluoresce. A charge-coupled device CCD camera looking down on the beam records the scattered light to reveal the path of the reflected atoms. The intensity of the fluorescence provides information about the relative number of reflected atoms.

Figure 5 shows the relative intensity of the fluorescence signal as a function of the angle α. The data point marked by a circle at zero angle is the fluorescence from the direct beam with the reflector moved to one side. This provides the reference intensity which we call unity. We see that all the atoms are reflected when the angle α is below 20 mrad. The signal drops as the angle is increased further, reaching a very

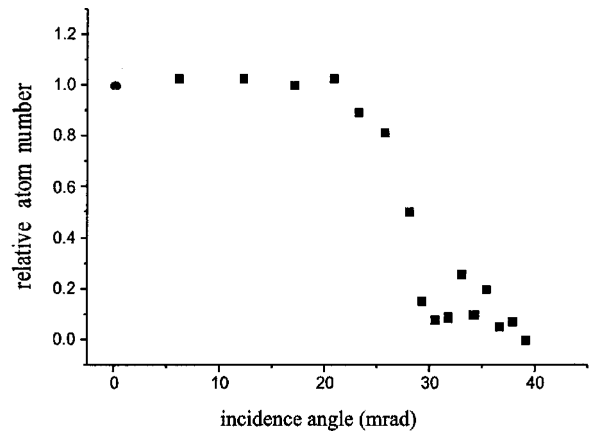

FIG. 5. Relative flux of atoms that have been reflected from the tape as a function of the angle of incidence at a longitudinal velocity of 75 m/s. The reflectivity starts to decrease for angles larger than ~20 mrad. This provides information on the magnetic field at the surface.

low level by 30 mrad. The small residual signal at these angles is due to a weak low-velocity tail in the velocity distribution of the atomic beam. The loss of reflectivity occurs because atoms that penetrate the repulsive magnetic barrier stick to the surface and are lost from the beam. At 50% reflectivity, the grazing angle α has the value 28 ± 1 mrad, where the error is a rough estimate based on the spread of the data points. There the normal velocity is 2.1 ± 0.1 m/s, indicating that the surface field of our reflector is 53 ± 5 mT: slightly less than the saturated value of 58 mT, as we would expect. The width of this step is due to the velocity distribution, the effect of angular spread in the beam being negligible. There is no evidence of excess width, which would occur if the mirror were not sufficiently flat.

As the atoms fly along the surface of the mirror they experience the spatially periodic magnetic field as a temporal oscillation at 2.5 MHz. This has the possibility of driving transitions between the magnetic sublevels, resulting in a much reduced reflectivity for the mirror. In order to avoid this effect, the data of Fig. 5 are taken with a bias field of 10 G applied along the z direction as indicated in Fig. 1. Without any bias, the intensity of the reflected beam is much smaller. Naively, one might expect that the bias field needs to exceed 7 G to maintain a splitting between sublevels that is larger than the 2.5 MHz oscillation frequency, which is why 10 G was used. However, we subsequently found that a smaller bias field of only 3 G still works well and we plan to investigate this further.

Our conclusion is that the flat grazing incidence mirror works extremely well. The surface field is as strong as one could expect, the reflecting potential is indeed flat, and the reflectivity is unity provided a suitable bias field is used.

B. Whispering gallery

The central goal of this experiment is to deviate the atomic beam through a large angle by multiple grazing reflections in a whispering-gallery geometry, shown in the inset in Fig. 6. Atoms moving on the arc of radius R experi-

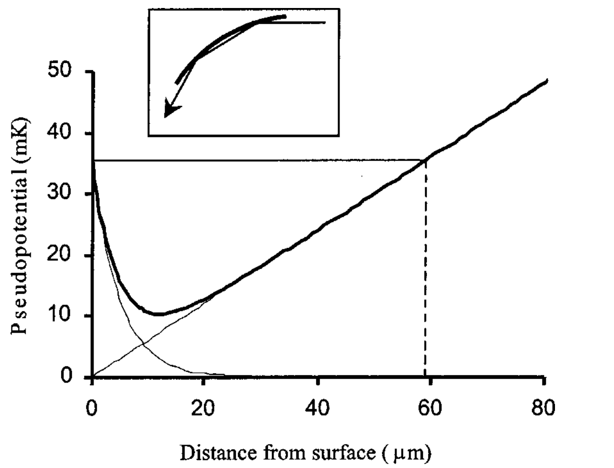

FIG. 6. Inset: The whispering-gallery geometry. Main graph: Pseudopotential for radial motion of the atoms.

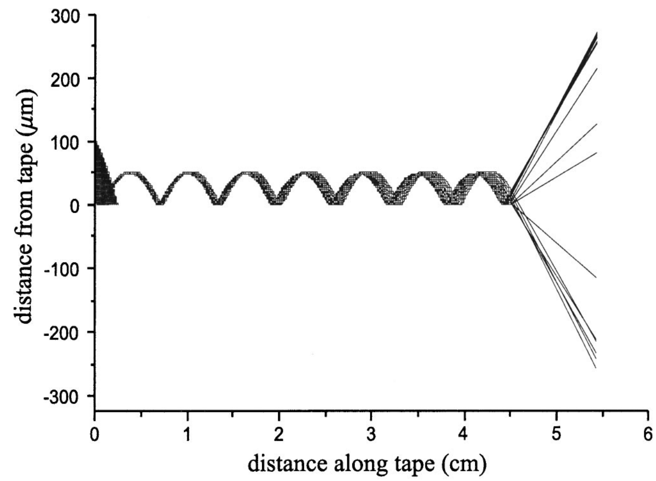

FIG. 7. Trajectories of the atoms along the reflector.

ence a centrifugal force $F = mv^2/R$, which gives rise to a pseudopotential at a small distance y from the surface of the tape. Adding this to the magnetic potential $\mu_B B_0 e^{-ky}$, one obtains the total pseudopotential for radial motion plotted in Fig. 6. Here we have taken B_0 to be 53 mT, as measured with the plane mirror, the radius of curvature is set to $R = 9.6$ cm (the smallest allowed by the curved rails shown in Fig. 3), and the beam velocity is 60 m/s, the velocity used in our whispering-gallery measurements. Atoms arriving parallel to the surface with impact parameters between 0 and $y_{\max} = 59$ μm are trapped within this potential and execute radial oscillations, which are the multiple bounces shown schematically in the inset of Fig. 6. Atoms incident with larger impact parameters hit the surface and are lost because they have more centrifugal energy than the 36 mK barrier at the surface. Thus the acceptance width of the whispering gallery is considerably narrower than the 150 μm width of the beam. By contrast, the angular acceptance of ± 35 mrad (at the center of the channel), corresponding to a radial velocity of ± 2.1 m/s (see Sec. III A above), is much larger than the angular spread of the beam.

When the entire acceptance width is filled with atoms close to zero angle, the ensemble has a broad range of radial oscillation frequencies because the pseudopotential is highly anharmonic. Correspondingly, the number of reflections is broadly distributed and the output beam has a wide angular dispersion. If, instead, the atoms are coupled in at a nonzero angle, so that their initial radial velocity is just slightly less than the critical 2.1 m/s, only those starting close to the minimum of the pseudopotential survive their first oscillation. For this much smaller region of phase space, the oscillation frequency is well defined. Figure 7 shows a calculation of such trajectories, taking an ensemble of atoms incident at $\alpha = 28$ mrad, i.e., with an initial radial velocity of 1.7 m/s. One sees that the dispersion in oscillation frequency is now quite small and generally all the atoms suffer the same number of reflections. In this simulation, the radius of curvature has been carefully chosen ($R = 9.0$ cm) so that some of the atoms undergo seven reflections before reaching the end of the tape while others bounce eight times. The number of reflections is easily understood using the following simple model. We approximate the inner part of the pseudopotential as a hard wall; then the radial acceleration is just the constant centrifugal one v^2/R. With our large input angle, the oscillations have almost the maximum amplitude $y_{\max} = 59$ μm and therefore the oscillation period is $(8 y_{\max} R/v^2)^{1/2}$. The time taken to travel through the whispering gallery is L/v, L being the 4.5 cm length of the tape. Consequently, the number of reflections is $1 + L/(8 y_{\max} R)^{1/2}$, which has the value 7.9 when the radius is 9 cm.

In the laboratory, we see that the distribution of the output beam is indeed strongly dependent on the initial angle α, as discussed above. For angles close to zero, we observe a rather diffuse output with complex structure corresponding to the many different oscillation frequencies in the pseudopotential. In order to set the input angle α close to the cutoff, we rotate the whispering gallery (around the vertical axis through the input end) until the flux of deflected atoms beam drops to $\sim 3\%$ of the straight-through beam. Once this is done, we find a beautiful sequence of output beams as the curvature is varied, each corresponding to a specific number of reflections in the whispering gallery up to a maximum of eight, which produce a deviation of $23°$. Figure 8(a) is a composite of six CCD images, showing a selection of output beams after two, three, four, five, and six reflections, as well

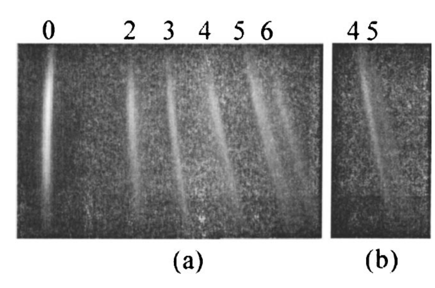

FIG. 8. (a) Superimposed images of the deflected atomic beam for two, three, four, five, and six reflections from the curved tape. The track labeled 0 is made by undeflected atoms. (b) A single image showing the double beam produced when some atoms have four reflections while others have five.

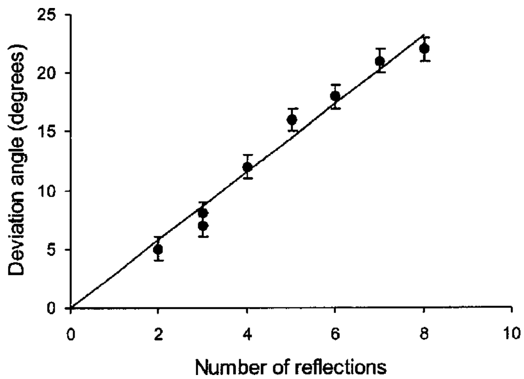

FIG. 9. Plot of number of bounces vs deflection angle.

as an image of the straight-through beam. One sees clearly that the whispering gallery works very well, producing angular deviations far larger than the plane mirror can make. The intensity of the deflected beams shows no dependence on the number of reflections, confirming that the reflectivity is unity and that the reflections are specular. At some intermediate curvatures, we are able to find double output beams where the last reflection is so close to the end of the tape that some of the atoms reflect there while others miss, as in the simulation of Fig. 7. An example of this is shown in Fig. 8(b) for the case of four and five bounces.

To the extent that the reflector is a hard cylindrical wall, each new reflection in the whispering gallery should produce an additional angular deviation of 2α. The tracks recorded by the CCD camera allow us to measure the deviation angles directly and these are plotted as a function of the number of reflections in Fig. 9, together with a least-squares linear fit. We see that the deflection does indeed grow linearly with the number of reflections and, on equating the slope of the line to 2α, we obtain the value $\alpha=25.3$ mrad. This is very reasonable, being slightly less than the 28 mrad expected for complete extinction of the beam.

IV. CONCLUSIONS

We have shown that videotape can be used as a high-quality atom reflector for grazing-incidence atom optics and we have used the atom beam itself to calibrate the strength of the magnetic field at the surface of the tape. We have also demonstrated that such a reflector now makes it possible to deflect an atomic beam traveling at 60 m/s through an angle as large as 23° by multiple reflections in a whispering-gallery geometry. In order to achieve this we have developed a technique for mounting the videotape so that the reflecting surface conforms closely to the desired shape and we have demonstrated that the shape can be reliably made flexible. In future we anticipate that this approach may be extended to make high-resolution optics for the manipulation of thermal atomic beams.

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