Rapid communication

Reflection of a slow cesium atomic beam from a naturally magnetized Nd-Fe-B surface

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Abstract. We have demonstrated the partly directed reflection of a slow cesium atomic beam by using the natural magnetic stray field above a Nd-Fe-B surface. From these experiments we determine the reflectivity and a minimum value for the magnetic stray field directly at the surface.

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In atom optics, atom-optical analogs of photonic optical components such as lenses, beamsplitters, and mirrors are fabricated [1]. There have been two main approaches in the construction of atomic mirrors: evanescent light waves [2] and spatially varying magnetic fields [3]. The first realization of an atomic mirror utilized an evanescent light wave [4]. During the last few years magnetic mirrors which use the Zeeman interaction between an atomic magnetic moment and an inhomogeneous magnetic field have become more and more popular. Flat atomic mirrors have been constructed using magnetic recording media [5], macroscopic permanent magnets [6, 7] and microfabricated electromagnetic devices [8]. Hughes et al. also formed curved magnetic mirrors from magnetic recording media [9, 10]. Recently, the focusing of atoms by using a curved magnetic mirror fabricated from video tape has been demonstrated [11]. Roach et al. also reported the high but not specular reflectivity of demagnetized audio tape [5].

All these magnetic mirrors are based on a periodic magnetization changing direction with a period of $\lambda$. This leads to an approximately exponentially decaying magnetic flux density above the magnetic surface [12, 13]. The decay constant is $2\pi/\lambda$ and the maximum surface field limits the normal atomic velocity that can be reflected. The construction of mirrors from magnetic recording media has the advantage of smaller magnetization periods and smoother equipotential planes. The advantage of mirrors fabricated from permanent magnets is that the magnetic field strength is an order of magnitude larger. Moreover the suppression of the magnetic field outside the material due to the finite thickness of the magnetic material is not relevant for bulk material, whereas this reduction is typically 30% for magnetic recording media.

The natural domain structure in ferromagnets which are not externally magnetized could provide a simple way to achieve both a high surface field strength of the order of 1 T and a magnetization period in the micron regime. Mirrors with these properties are needed for magnetic imaging schemes with laser-cooled atomic beams in grazing-incidence geometries.

In the absence of external fields the demagnetized state is the stable state in large ferromagnetic crystals and for this state the free energy is minimal. The resulting domain structure is then a consequence of balancing various contributions to the free energy in order to minimize it [14]. For our purpose the most interesting contribution is the anisotropy energy. It arises from the existence of preferred (“easy”) axes of magnetization in ferromagnetic crystals. No domains of closure can form in a specimen with very strong magnetic anisotropy and only one easy axis orientated perpendicular to one of its surfaces exists. Consequently a magnetic field leaks out and forms a stray field immediately above the surface. The internal and surface domains will then self-organize in order to minimize the contribution of the magnetic stray field to the free energy. This results in a domain pattern with alternating magnetization which is in one dimension similar to an atomic mirror built from permanent magnets.

In this paper we describe the surface properties and magnetic stray field of a naturally magnetized Nd-Fe-B surface. We then use this field to reflect a Zeeman-slowed cesium atomic beam.

1 Surface preparation and characterization

A sintered Nd-Fe-B cuboid with dimensions $90 \times 30 \times 10 \text{ mm}^3$ was obtained from Magnetafabrik Schramberg [15]. The cuboid was polished with abrasive paper and a fine finish was accomplished using crystal polish powder. Figure 1a shows a difference interference contrast image of the surface, which was used to obtain a general overview.
Fig. 1. a Difference interference contrast image of the polished Nd-Fe-B surface. Bright regions are flat areas and dark regions are grooves. b Magnetic domain structure of the squared region in a imaged with a polarizing microscope. The axis of easy magnetization is perpendicular to the surface shown. c Same region imaged with a magnetic force microscope. One can clearly see that both techniques show the same domain structure. Approximately 80% of the surface is flat, whereas the remainder contains cavities. Further polishing did not reduce the portion of the surface covered with cavities because sintered Nd-Fe-B is only 97% dense. For a quantitative analysis we inspected the flat parts of the surface by means of atomic force microscopy (SIS Ultra objective). The rms roughness of the surface was determined to be 50 nm on a 20 × 20 μm² scale and reduces to 7 nm on a 5 × 5 μm² area. This is to be compared with a rms roughness of 100 nm for the original unpolished surface. Once polished the material has to be kept under vacuum conditions because the effect of corrosion upon Nd-Fe-B magnets is serious.

The sintered Nd-Fe-B material consists primarily of aligned grains of the tetragonal Fe₄Nd₂B phase. These grains possess a high magnetic anisotropy with the easy axis being normal to the polished surface. The material also contains non-magnetic secondary grain boundary phases into which excess Nd and B atoms diffuse. Typical values for the grain size are 5–10 μm. Magnetic domains were observed by using a magnetic force and a polarizing microscope at normal incidence on the polished surface. Owing to the Kerr effect, domains with different direction of magnetization appear as dark and bright regions [16]. The spontaneous magnetization $M_S$ of the domains is $M_S = 1.63 \text{T/μμ}$ [17]. Figure 1b shows the typical dendritic domain structure of a Nd-Fe-B surface [18]. Domains in the surface grains are subdivided to reduce magnetostatic energy. This is also accomplished by additional small point-like domains inside larger domains, which can be clearly seen in Fig. 1b, c. From these images we determine a mean lateral size of the magnetic domains of approximately 1 μm. A one-dimensional periodic arrangement of the domains would result in a decay of the lowest spatial Fourier component of the stray field with a decay length of roughly 0.2 μm. However, due to the stochastic domain structure it seems feasible that also lower spatial Fourier components exist, leading to a slower decay of the stray field.

2 Experiment

Our beam source (Fig. 2) is a Zeeman-slower which produces a slow and cold cesium atomic beam with a mean longitudinal velocity in the range 35 to 120 m/s, a longitudinal velocity spread of less than 1 m/s, and a current of about 1 × 10¹⁰ atoms/s [19]. The final atomic beam has a diameter of 3 mm and a transverse velocity width below the Doppler limit, which corresponds to 12.5 cm/s for cesium. All the atoms are in the $F = 4$ substate. An optical polarization stage is used to pump all the atoms into the outermost $m_F = +4$ Zeeman state, which has a constant magnetic moment of 1 μμ. For detection, the fluorescence of atoms traversing a sheet of resonant laser light is imaged onto an intensified CCD camera.

The setup for the reflection experiment is housed in a second vacuum chamber connected to the source chamber. The Nd-Fe-B cuboid is placed on an electrically driven rotation stage (angular resolution better than 0.3 mrad) which is connected to a translation stage. This translation stage allows us to move the whole assembly perpendicular to the atomic beam axis. Two movable apertures were used to align the magnetic surface parallel to the atomic beam axis to better than 1.7 mrad.