Microfabricated magnetic structures for cold atom optics

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The development of high-quality, coherent atomic mirrors is a very important aspect of the burgeoning field of cold atom optics. Atomic mirrors based on evanescent-wave light fields appear to have been refined about as much as can be expected, but they are still not good enough for coherent atom optics experiments. The recent development of atomic mirrors based on periodic magnetic structures offers an alternative approach, which has the potential for producing high-quality atomic mirrors.

We have successfully operated mirrors based on arrays of millimetre-thick permanent magnets [1] and current-carrying conductors [2], but there is a need for high-quality elements with micron-scale magnetic structures. Such devices have the potential to provide flatter mirrors with smaller dispersive phase shifts, and to allow the generation of magnetic diffractive elements.

The magnitude of the magnetic field at distance y above an infinite array (with period a in the x direction) of magnets of thickness b is

$$B(x,y) = B_0 e^{-ky}[(1-e^{-kb}) + \frac{1}{3}(1-e^{-3kb})e^{-2ky} cos2kx + ...] \quad (1)$$

where the decay length $k^{-1}{=}a/2\pi$. Sufficiently far above the array the magnitude of the magnetic field is independent of x and falls off exponentially with y.

We have followed parallel approaches to developing micron-scale magnetic elements, involving the fabrication of periodic magnetic structures recorded onto TbFeCo magneto-optical film [3], and of periodically grooved structures produced by electron-beam lithography and replication techniques.

Because in magneto-optical films the magnetization is perpendicular to the plane of the film, magneto-optical magnetic mirrors complement other mirrors based on magnetic recording media [4, 5] and offer the prospect of writing finer structures ($<1\mu$m) with higher magnetic homogeneity.

Magnetic structures with periodicities down to 1.2μm have been ruled on $Tb_{.15}Fe_{.79}Co_{.06}$ magneto-optical films in the presence of an applied perpendicular magnetic field using a tightly focussed diode laser mounted on a modified optical diffraction grating ruling engine. These films have a remanent field of 2.4 kG, coercivity 1.1 kOe, Curie temperature 230C, and thickness b=0.18μm. Magnetic force microscope images confirm that the ruled regions were uniformly magnetized and that the magnitude of the magnetic field falls off exponentially with distance y above the mirror with decay constant $2\pi/a$.

Time-of-flight measurements on a beam of laser-cooled, ground-state F=4 caesium atoms suitably optically pumped and dropped from a height of about 18 mm onto the surface of the magneto-optical mirrors were found to produce strong reflection signals, suggesting up to 100% reflectivity after allowing for geometrical factors. Measurements using a CCD camera of the spatial distribution of the incident and reflected atoms at various heights above the mirrors indicate that, while the reflection is predominantly specular in character, there is a diffusive component introduced by the reflection process. This suggests that the magnitude of the magnetic field just above the surface (100 to 150 gauss) is such that there is a significant contribution from the x-dependent *corrugation* term in Eq (1). We believe the magnetic properties for this particular magneto-optical film composition contribute to the weaker than desirable field. The shape of its magnetic hysteresis loop is far from ideally square, so some demagnetization can occur even at room temperature in the magnetic field applied during the ruling process. This is exacerbated by heat diffusing out of the region being ruled, a consequence of the low recording speeds required for the relatively thick films. A magneto-optical film with better magnetic characteristics should work better.

Magnetic microstructures have also been produced using electron beam lithography and replication techniques to fabricate square-grooved structures to a depth of around 0.5μm on the surface of ferromagnetic materials. The magnetic field above such a surface is essentially as given by Eq(1), without requiring the production of regions of alternating magnetization. Structures with periods down to 0.7μm in cobalt, nickel and Alnico have been magnetized in-plane, perpendicular to the groove direction. They have proven to be difficult to magnetize completely, and only weak reflection of caesium atoms (30%) has been observed [6]. Recently, a variation of this technique, using a Co-Cr alloy, has shown much more promise, and magnetic force microscope images indicate more uniform magnetization and stronger fields above the surface than for the ruled magneto-optical films. Results from these structures will be presented.

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[1] A.I. Sidorov, R.J. McLean, W.J. Rowlands, D.C Lau, J.E. Murphy, M. Walkiewicz, G.I. Opat and P. Hannaford, *Quantum Semiclass Opt* **8** 713 (1996).

[2] D.C. Lau, A.I. Sidorov, G.I. Opat, R.J. McLean, W.J. Rowlands and P. Hannaford, *Eur. Phys J.* **5** 193 (1999).

[3] D.C. Lau, R.J. McLean, A.I. Sidorov, D.S. Gough, J. Koperski, W.J. Rowlands, B.A. Sexton, G.I. Opat and P. Hannaford, *J.Opt.B* **1** 371 (1999).

[4] T. Roach, H. Abele, M.G. Boshier, H.L. Grossman, K.P. Zetie and E.A. Hinds, *Phys.Rev.Lett* **75** 629 (1995).

[5] I.G. Hughes, P.A. Barton, T.M. Roach, M.G. Boshier and E.A. Hinds, *J.Phys.B* **30** 647 (1997).

[6] A.I. Sidorov, D.C. Lau, G.I. Opat, R.J. McLean, W.J. Rowlands and P. Hannaford, *Laser Physics* **8** 642 (1998).