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MATTER-WAVE INTERFEROMETRY WITH LASER COOLED ATOMS

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This research program is concerned with matter-wave interferometry of laser cooled atoms. A slow beam of laser cooled rubidium atoms will be used as the matter-wave source. The atom optical elements are microfabricated amplitude transmission gratings which will be used in a three-grating interferometer to split and recombine the rubidium beam. The atomic interferometer will be a useful new tool with which to perform precision experiments in atomic physics, quantum optics, and gravitation.

The research program takes advantage of three new technologies, the combination of which provides a unique opportunity to construct a compact and stable interferometer. The techniques of laser cooling and trapping are used to produce cold rubidium atoms in a well collimated beam. Commercially available diode lasers with optical feedback frequency stabilization are used for the laser cooling and trapping beams and for atomic beam diagnostics. Finally, submicron transmission gratings made with high-resolution electron-beam lithography are used as the coherent beam splitters of the atomic interferometer. Figure 1 shows the proposed interferometer geometry with the two paths that are generally used in such a device. The three-grating Bonse-Hart interferometer is a particularly useful design since it has intrinsically equal path lengths and is relatively insensitive to misalignments.[1,2] Figure 2 shows a schematic of our experiment in which the matter-wave source is a laser cooled rubidium atomic beam.

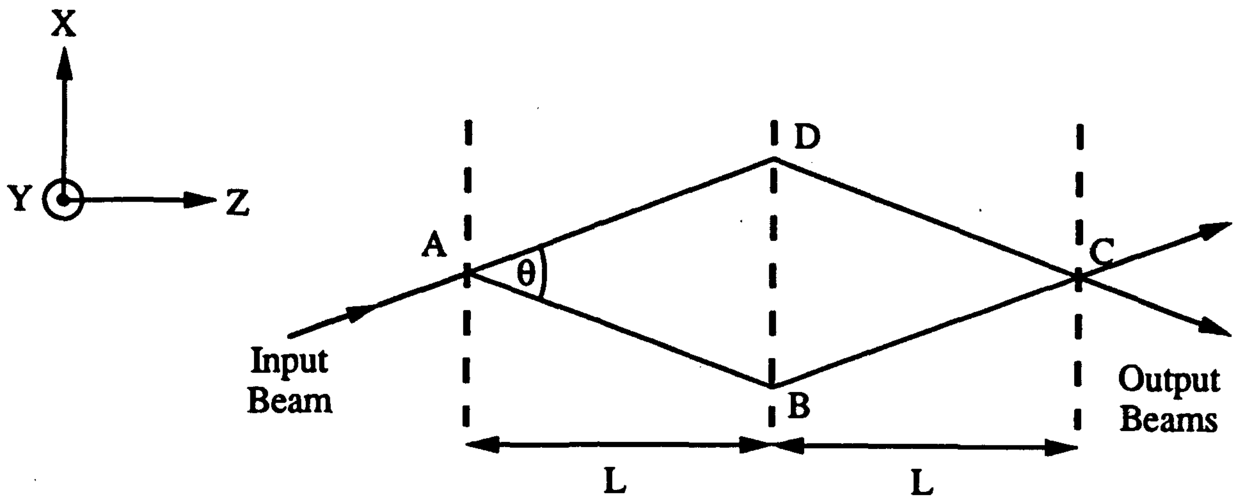

Fig. 1. Three-grating Bonse-Hart interferometer with two-path interference configuration shown.

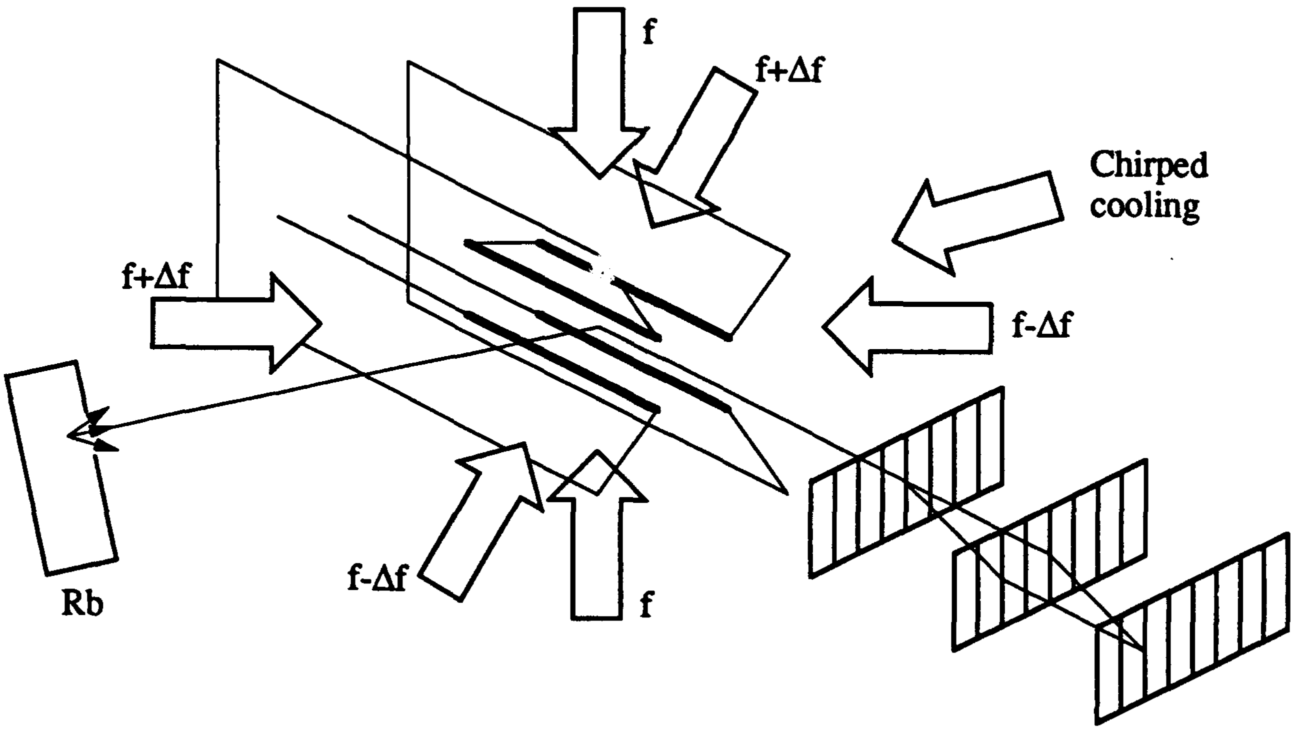

Fig. 2. Experimental schematic for three-grating interferometry with laser cooled atomic beam. The pieces of the magnetic field coils shown in bold are the ones mainly responsible for the two-dimensional quadrupole field forming the funnel.

During the past twelve months of this grant (8/1/93 - 7/31/94) we have been working primarily on the matter-wave source. We have produced a cold beam of atoms from the two-dimensional trap.

As shown in Fig. 2, rubidium atoms from the oven are slowed and cooled by the scattering force from a counterpropagating laser beam tuned below the $F = 3$ to $F' = 4$ hyperfine transition of the D_2 line of ^{85}Rb. During the cooling, the laser frequency is ramped toward the resonance frequency to compensate for the decreasing Doppler shift of the decelerating atoms.[3,4] By adjusting the frequency of the laser at the end of this ramp, we can control the characteristic velocity of the cooled beam, which is important for loading the atoms into a trap.[5] A second chirped diode laser is used to counteract optical pumping of the atoms to the other hyperfine level of the ground state.

The slow atoms drift into a two-dimensional magnetic quadrupole field in which six laser beams intersect to form a two-dimensional magneto-optic trap or so-called atomic funnel.[6,7] The coils that produce the two-dimensional quadrupole magnetic field are shown in Fig. 2. The funnel is presently oriented horizontally. Figure 3 shows a schematic of the experiment as viewed from above. The atoms experience molasses-type damping in all three dimensions and are trapped in the two dimensions transverse to the axis of the trap. Along the axis of the trap, the atoms move with a velocity determined by the intersecting laser beam frequencies. Three lasers at frequencies f and $f \pm \Delta f$ are used, with the laser at frequency f used for the vertical pair of beams. In the horizontal plane, the laser beams are aligned at 45° with respect to the funnel axis, with the two beams coming toward the funnel output beam at frequency $f - \Delta f$ and the two beams coming from behind at frequency $f + \Delta f$. This should produce a beam of atoms moving along the axis of the magnetic field with a mean velocity of $\sqrt{2}\,\Delta f\,\lambda$. The three lasers are each frequency-offset locked to a fourth reference laser that is stabilized to a rubidium absorption cell using polarization spectroscopy. Thus we can independently change the detuning of the mean laser frequency f with respect to the atomic resonance frequency f_0 to optimize the cooling and trapping, as well as the

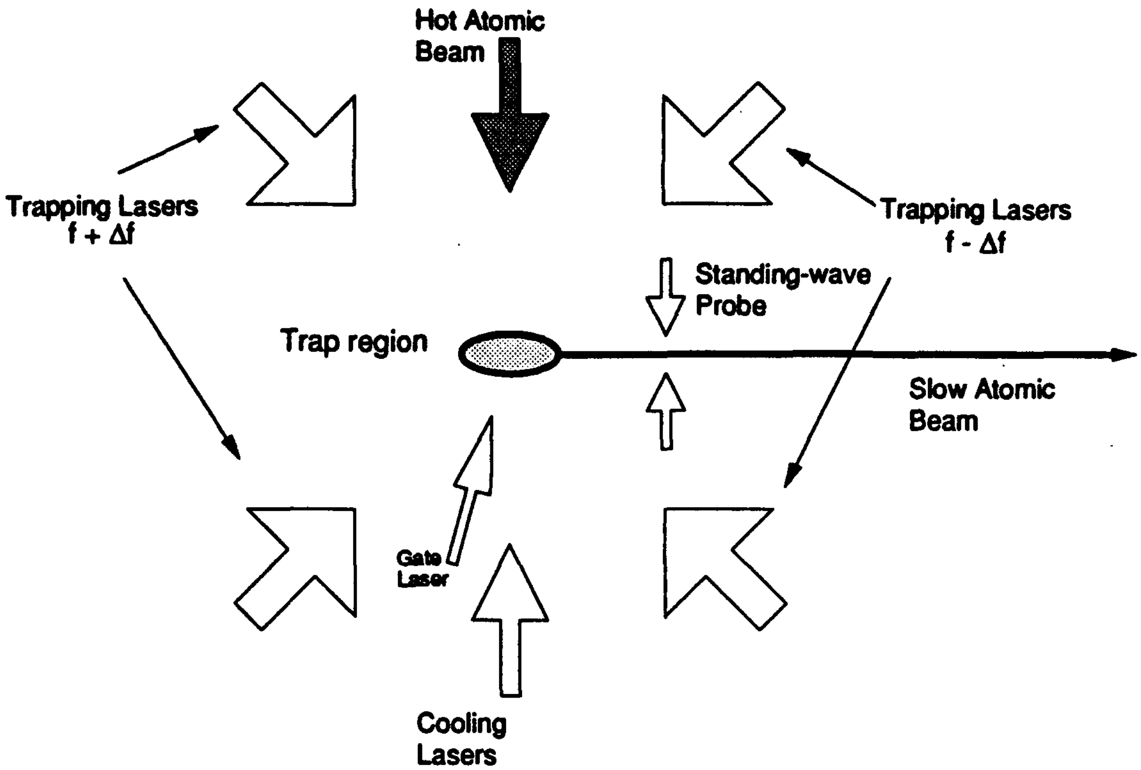

Fig. 3. Top schematic view of the atomic funnel. Not shown are the counterpropagating vertical lasers at frequency f and the coils used to create the two-dimensional quadrupole magnetic field.

detuning Δf that controls the funnel beam velocity. The frequency offset locking system described above leads to a range of possible beam velocities of 2 - 33 m/s. Velocities much less than 10 m/s are too strongly influenced by gravity to be used in a horizontal interferometer but could be used in a vertical geometry. All the lasers used in this experiment are diode-lasers that use diffraction gratings as an optical feedback element.[8] These lasers have a FWHM linewidth of 150 kHz.[9] When frequency-offset locked together, they have relative jitters of 10 kHz, which is very important for a well defined velocity of the slow beam.

Atoms in the funnel are monitored by viewing their fluorescence with a CCD camera and a photomultiplier. Atoms that leave the funnel along the axis will enter a region with no laser fields and so will not fluoresce. To detect these atoms, we have introduced a horizontal standing-wave laser field approximately 1 cm beyond the end of the funnel, as depicted in Fig. 3. With red detuning, this standing wave also provides one-dimensional transverse molasses damping of the atomic beam. Figures 4 and 5 show digitized video images of the funnel and downstream molasses region, viewed from the side and from the top, respectively. The side view (Fig. 4) shows the transverse spread of the beam as it travels downstream. That spread implies a one-dimensional transverse temperature of approximately 500 μK. The other transverse dimension is seen in the top view (Fig. 5). In this dimension, the transverse molasses plays a role. There is still enough magnetic field gradient in this region to permit magneto-optic trapping to be effective, which explains why the downstream beam can be nearly the same size as the beam in the funnel.

To determine the velocity of the slow atomic beam, we have done a time-of-flight experiment. A resonant traveling-wave laser beam (gate laser in Fig. 3) is directed into the funnel and its radiation pressure deflects the atomic beam strongly to the side. The frequency of this beam is then quickly changed to effectively turn off this gating laser, allowing the funnel to operate unimpeded. The downstream probe region is then imaged onto a photomultiplier so that the arrival time of the gated atoms can be measured. If we assume that the velocity is constant between the gate region and the probe region, then we obtain the results shown in Fig. 6, where we have plotted the beam velocity as a function of the detuning Δf. The theoretical line is $v = \sqrt{2}\ \Delta f\ \lambda$ as discussed above. Discrepancies between the data sets and with the theory may be due to axial magnetic fields, laser beam intensity imbalances, or beam misalignments. We are still investigating these effects.

From the magnitude of the photomultiplier signal we have estimated that there are 10^7 atoms in the funnel each time it is loaded. With a chirp frequency of 25 Hz, we thus have 2.5×10^8 atoms/s in the slow beam. Atoms loaded from one chirp are ejected from the trap well before atoms from the next chirp arrive.

We are now preparing to put the diffraction gratings into the vacuum chamber. The amplitude transmission gratings have a period of 250 nm and are made from free-standing silicon nitride films on silicon substrates.[10] The three gratings will be separated by 5 cm and will diffract

Fig. 4. Digitized video image of atoms in the atomic funnel. This side view shows the funnel at the left and the downstream probe region to the right. One of the wires (1/8" diameter) used to make the quadrupole magnetic field is visible near the top of the image.

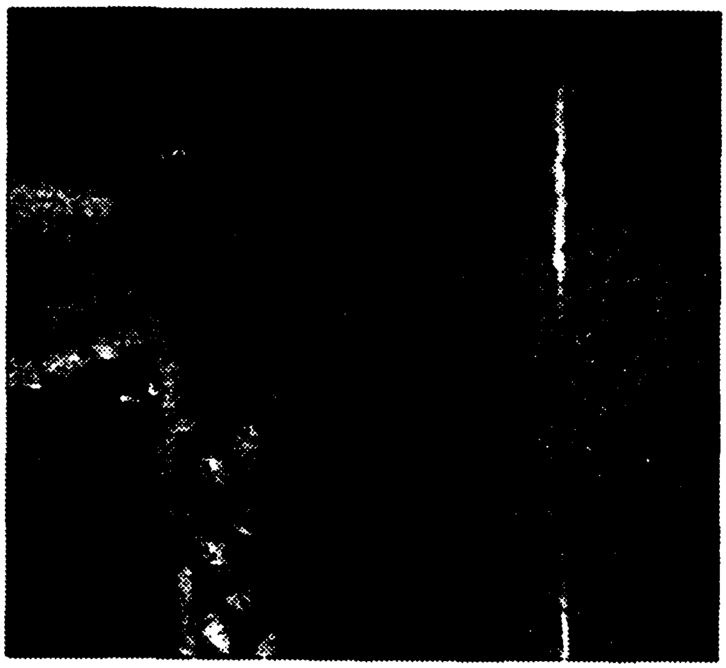

Fig. 5. Digitized video image of atoms in the atomic funnel. This top view shows the funnel at the bottom right and the downstream probe region at the upper right. One of the wires (1/8" diameter) used to make the quadrupole magnetic field is visible on the left side of the image.

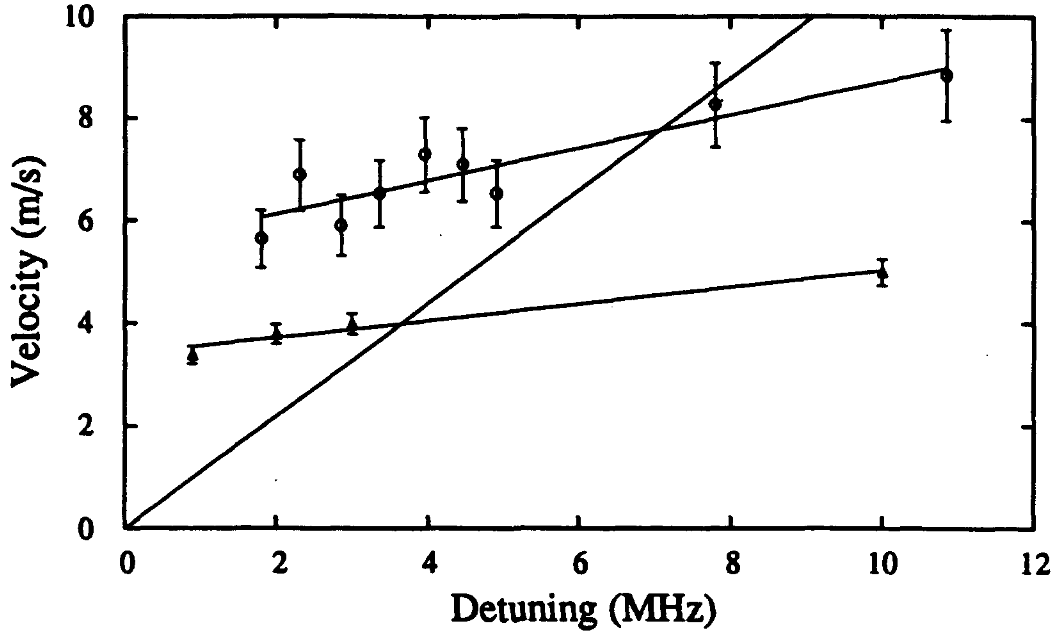

Fig. 6. Time-of-flight data showing velocity as a function of laser detuning. The circles and triangles represent data from two separate runs, with the corresponding solid lines being linear least squares fits. The third solid line is the theoretically expected curve.

the rubidium beam by 2 mrad into the first order. Compared to the other interferometers which have been demonstrated using material structures,[11] ours is relatively compact. The ability to tune the velocity of the funnel output beam also provides our experiment with another degree of flexibility.

A report on the atom interferometer work was presented at the 1994 International Quantum Electronics Conference, Anaheim, California, May 8-13, 1994,[12] and will be presented at the Fourteenth International Conference on Atomic Physics, Boulder, Colorado, July 31- August 5, 1994.[13] A paper on the optical stabilization of a diode laser to an atomic resonance was published[14] and a report was presented at the 1993 Interdisciplinary Laser Science Conference (ILS IX), Toronto, Canada, October 3-8, 1993.[15]

During the 1993-1994 academic year there were two graduate students working full time on this research. Both were funded by this grant. Three graduate students were working part time on this research, funded by department teaching assistantships. During this summer, four graduate students are working full time on this research. Three are funded by this grant and one is funded by a department fellowship. One student completed a M.S. thesis during the past year.

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