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MATTER-WAVE INTERFEROMETRY WITH LASER COOLED ATOMS

David McIntyre

Department of Physics, Oregon State University, Corvallis, OR 97331

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This research program is investigating matter wave interferometry with 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.

During the past twelve months of this grant (8/1/91-7/31/92) we have been working in parallel on the laser-cooled atomic rubidium beam and fabrication of submicron amplitude transmission gratings.

The matter wave source for this experiment will be a cold beam of rubidium atoms leaving an atomic funnel.[1] The funnel uses two-dimensional magneto-optic trapping to achieve transverse cooling as well as spatial compression of the beam. With laser beams from all six directions, the atoms are also cooled, but not trapped, along the axis of the magnetic field. We have two ideas we are pursuing for loading atoms into the funnel. The first is to use atoms from a thermal (200 °C) beam which are cooled longitudinally with chirped laser cooling.[1] The second is to use a room temperature vapor cell and load atoms from the low velocity tail of the Maxwellian distribution.[2] The second idea would simplify the experiment since the chirped laser cooling could be skipped. The question is whether the vapor cell funnel can produce a beam as intense as the funnel loaded from the cooled atomic beam.

In the past year we have completed construction of a two-chamber differentially pumped vacuum system to house the atomic beam and the interferometer. The source chamber is pumped with a turbomolecular pump and has a base pressure of 2×10^{-8} Torr and an operating pressure of 6×10^{-7} when the rubidium oven is heated to produce the beam. The high vacuum experimental chamber is pumped with a diffusion pump and has a base pressure of 3×10^{-9} Torr. We have operated the atomic beam and have detected rubidium atoms using a hot wire detector. We are now beginning our effort to slow the beam using chirped laser cooling.

To refine our laser cooling and trapping techniques and to test the vapor cell funnel idea, we have also constructed a small rubidium vapor cell and have cooled and trapped atoms in a magneto-optic trap. The vapor cell trap is shown in Fig. 1, with rectangular coils used to produce a two-dimensional quadrupole magnetic field in the vicinity of the overlapping laser beams. This trap operates at various angles between the field symmetry axis and the laser beam axes, without changing the polarization states of the laser beams. A pure two-dimensional quadrupole magnetic field, with no longitudinal field gradient, should not trap the atoms longitudinally. However, we do observe a confinement of the atoms along the trap axis, presumably due to field imperfections. Figure 2 shows a digitized video image of the trapped atoms' fluorescence. The structure in the trap may be due to magnetic field inhomogeneities or laser beam intensity structure. We have spatially filtered the laser beams to remove some of this structure, but it is difficult to remove all of it due to disruptive feedback into the laser from the pinhole.

A cold beam of atoms can be produced from this trap by frequency shifting some of the laser beams to create a "walking" trap. In the original funnel experiment,[1] the axial beams were frequency shifted. However, since we need to have the interferometer downstream, we plan to rotate the axial pair of beams and one transverse pair by 45° (as shown in Fig. 1) and frequency shift the two resulting pairs of forward and reverse beams, as shown in Fig. 3. This will produce a beam of atoms moving along the axis of the magnetic field with a mean velocity of $\sqrt{2}\,\Delta f\,\lambda$. Three separate diode lasers will be used for the three pairs of beams.

The vapor cell trap uses laser diode systems with optical feedback stabilization from Fabry-Perot confocal cavities.[3] In the past year we have also built and tested lasers which use diffraction gratings as the feedback element.[4] These lasers are simpler to implement and have comparable performance. We use 1800 *l*/mm holographic gratings, which are placed at the Littrow angle about 3 cm in front of the collimated laser diode. The laser diode, collimator lens, and grating are all mounted on an aluminum block which is temperature stabilized. This helps to improve the mechanical rigidity of the laser. The grating is tilted with a screw and a piezoelectric transducer to provide coarse ($\approx \pm 5$ nm) and fine ($\approx \pm 3$ GHz) tuning of the laser, respectively. The linewidths of these lasers are at or below the MHz level. We have built four such laser systems and have four more under construction.

We have fabricated amplitude transmission gratings to be used for the atomic interferometer. We started to do this work locally, but had enough trouble with some of the processing steps that we decided to do the work at the National Nanofabrication Facility (NNF) at Cornell University. The gratings were fabricated using the series of processing steps shown in Fig. 4.[5] A <100> oriented silicon wafer which is polished on both sides is first coated on both sides with 120 nm of silicon nitride using low pressure chemical vapor deposition (LPCVD). Free standing membranes or windows of the silicon nitride film are made by using optical lithography to pattern the back side of the wafer, reactive ion etching (RIE) in CF_4 to remove the patterned nitride, and a hot, wet etch in KOH to remove the exposed silicon. Figure 5 shows a scanning electron microscope (SEM) picture of the hole etched in the silicon, with the free-standing membrane at the bottom of the hole. The wet KOH etches very slowly along the <111> crystal planes, producing the beveled hole. The gratings are defined on these membranes using a JEOL JBX-5DII(U) electron-beam lithography system. Before exposure, the wafer is coated on the front side with 200 nm of polymethylmethacrylate (PMMA) and a thin (≈ 20 nm) layer of gold to reduce writing distortions caused by substrate charging. The grating pattern is written in successive 80 μm "fields", with computer control to ensure that the fields are properly "stitched" together. After the grating is exposed, the PMMA is developed to leave a mask. The exposed silicon nitride is then removed using a reactive ion etch which was developed to be more selective and highly directional.[5] Figure 6 shows an SEM micrograph of part of a grating with a 250 nm grating spacing.

We have fabricated gratings with periods of 250 nm and 500 nm and with total areas of 1 mm x 150 μm, 1 mm x 50 μm, 0.5 mm x 150 μm, and 0.5 mm x 50 μm. Each 3" wafer is divided into 20 8 mm x 18 mm chips. Each chip has six atomic scale gratings, two larger optical scale gratings, and a marker window as shown in Fig. 7. We fabricated a total of 25 useable chips. We were not as successful with the larger optical gratings ($d = 8.4$ μm) as with the atomic gratings. We designed the optical gratings for use in optical alignment of the interferometer and made the windows 1 mm x 1 mm in area, thinking that we could simply scale up the atomic gratings. However, the thickness of the nitride layer was obviously not scaled up, and this led to destruction of many of the optical gratings during the last RIE step. We tried several methods and did meet with some success, though it was inconsistent. To prevent this destruction we separately tried increasing the number of support bars and decreasing the open fraction of the gratings. We also tried reducing the e-beam exposure so that the silicon nitride would not etch completely through, leaving a phase grating, and coating the backside of the membrane with aluminum oxide before the last RIE, also leaving a phase grating. Not one of these variations worked consistently, though each did work once or twice in test runs.

To test the coherence of the gratings we arranged for the e-beam system to write verniers on the silicon substrate. By comparing verniers written in adjacent fields, we could determine the stitching errors. We found that the fields were correctly placed to within 10 nm between subsequent fields and to within 50 nm overall. Since this is a small fraction of the 250 nm grating spacing, the gratings are quite coherent.

Reports of this work were presented at the annual Division of Atomic, Molecular, and Optical Physics (DAMOP) Meeting of the American Physical Society, Chicago, Illinois, May 19 - 22 1992, and will be presented at the Thirteenth International Conference on Atomic Physics (ICAP-XIII), Munich, Germany, August 3-7, 1992.

During the 1991-1992 academic year, there were five graduate students and three undergraduate students working part time on this research. One graduate student and three undergraduate students were supported by this grant. (Two of the undergraduate students were supplemented by federal work study funds). The other graduate students were funded by department teaching positions (1) and fellowships (3). During this summer, there are five graduate students and two undergraduate students working full time on this research. Three of the graduate students are funded by department fellowships; the rest are funded by this grant.

References

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[4] C. E. Wieman and L. Hollberg, Rev. Sci. Instrum. **62**, 1 (1991).

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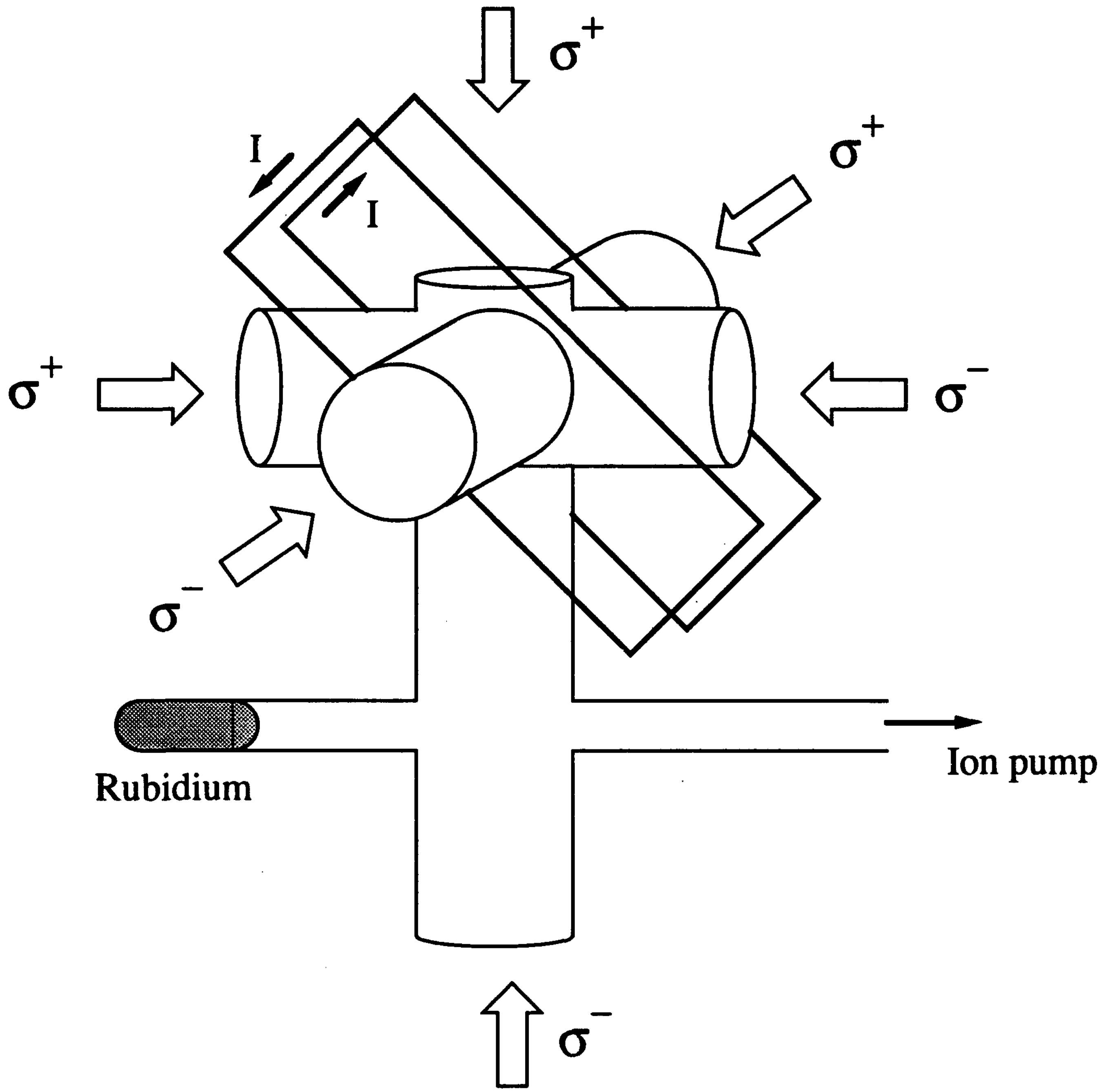
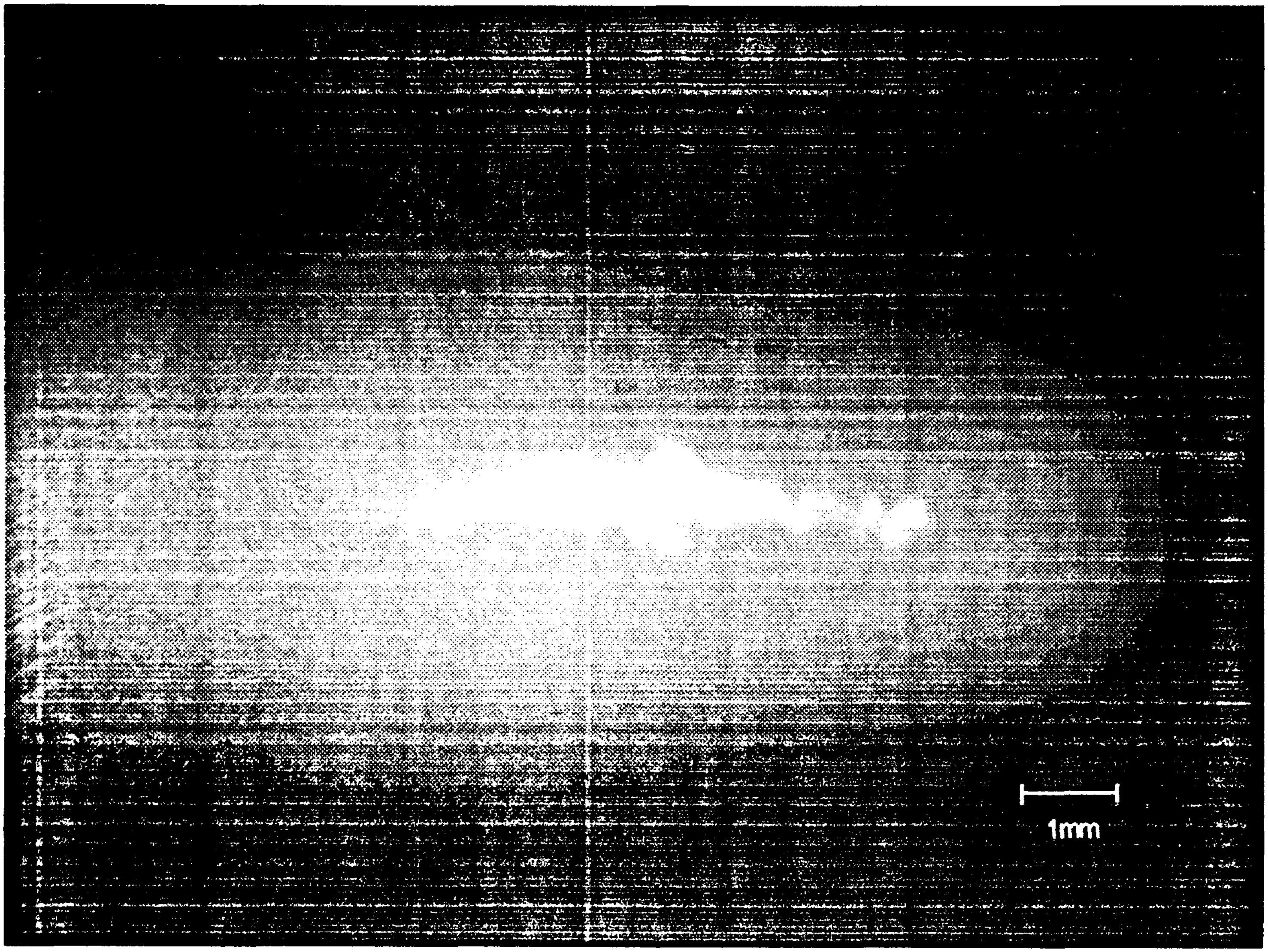


Figure 1: Schematic of rubidium vapor cell used for magneto-optic trapping of atoms. Rectangular coils produce a two-dimensional quadrupole magnetic field. Circularly polarized laser beams are detuned to the red side of the cycling transition to cool and trap the atoms.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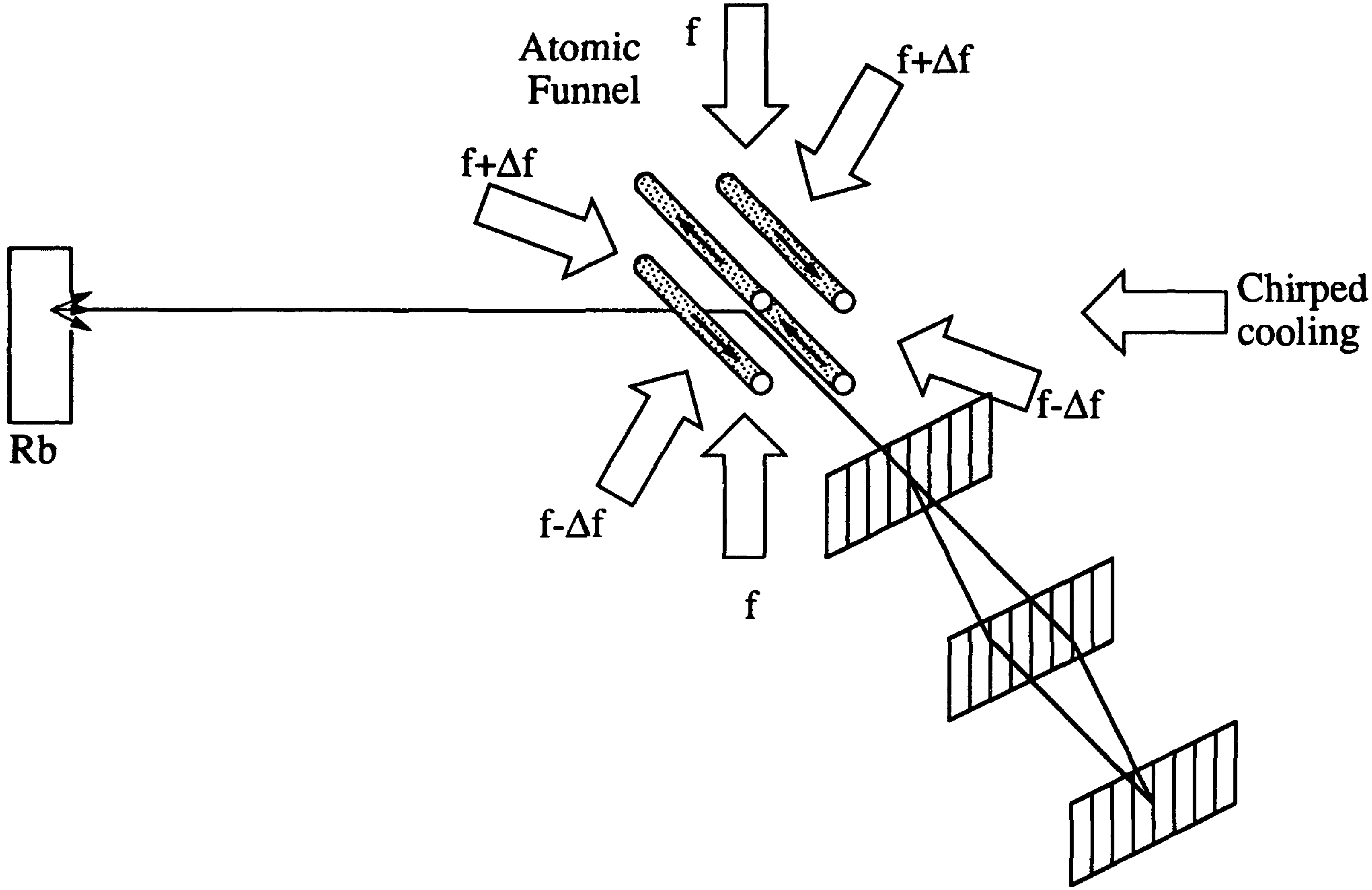

Figure 3: Schematic diagram of proposed atom interferometer experiment. Atoms from a thermal (200 °C) rubidium beam are cooled longitudinally and drift into the atomic funnel. The laser frequencies shown will produce a beam of atoms moving along the axis of the magnetic field, sending it into the three grating interferometer.

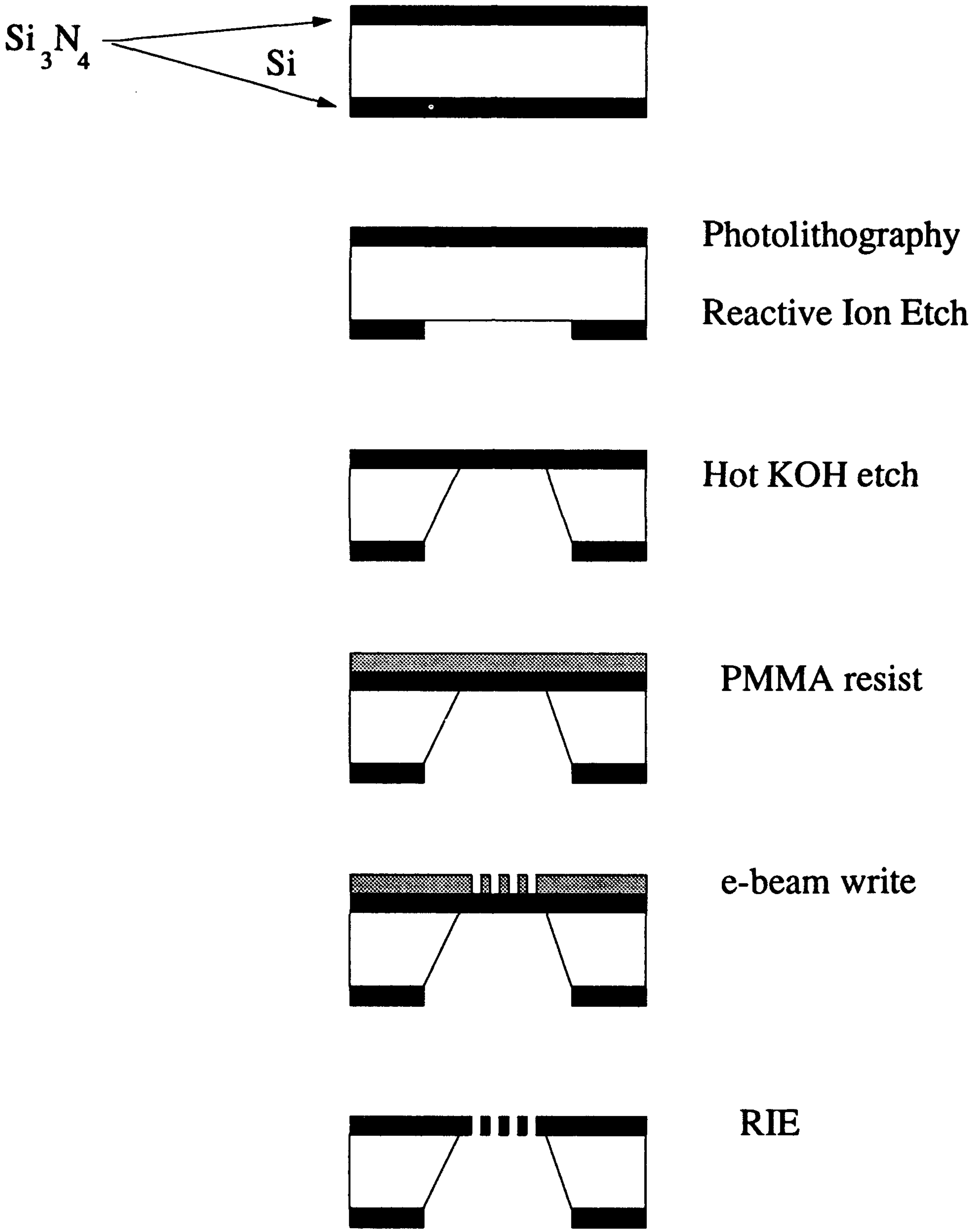

Figure 4: Schematic diagram of grating fabrication processes.

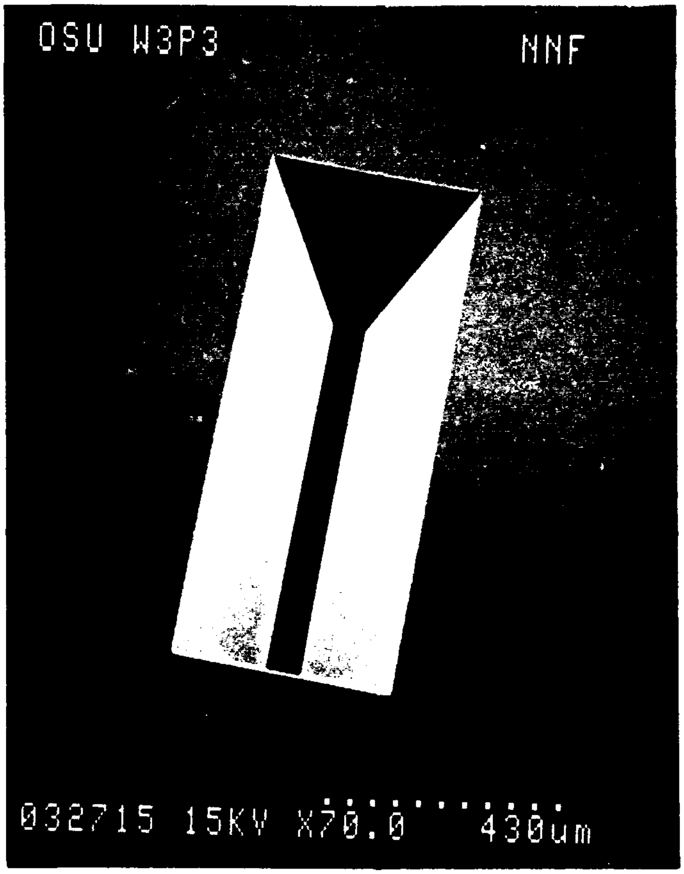

Figure 5: SEM micrograph of a window etched in the silicon wafer. The free standing membrane at the bottom of this window is 1 mm x 50 μm.

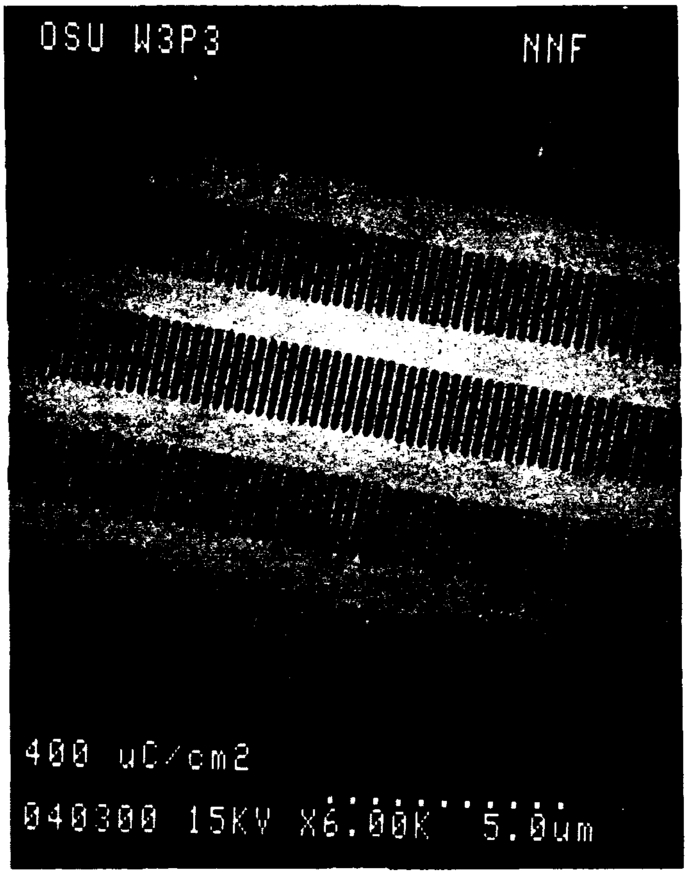

Figure 6: SEM micrograph of a grating fabricated in a free-standing silicon nitride membrane. The grating spacing is 250 nm, and the spacing of the horizontal support bars is 4 μm.

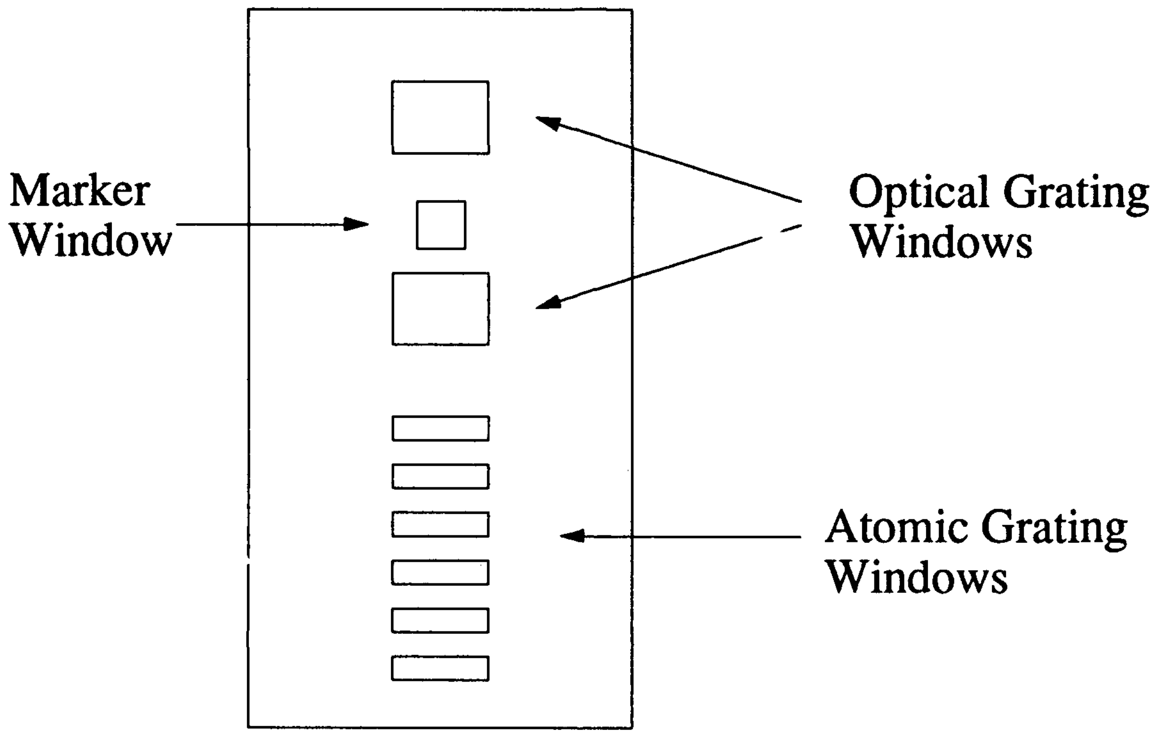

Figure 7: Pattern used in photolithography to define windows in silicon nitride.