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13. ABSTRACT *(Maximum 200 words)*

Work by Prof. Pritchard and his collaborators is summarized here.

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David E. Pritchard

Atom Wave Interferometer
Grant No. N00014-89-K-1207
December 1, 1988 through November 30, 1991
Final Report

The biggest accomplishment during the current grant period was the demonstration of a three grating interferometer for atoms — the first true atom interferometer reported in the literature. Accomplishments in several areas were essential to realizing our interferometer: grating fabrication construction of a vibration isolation/position servo, development of a suitable grating alignment scheme, development of an improved detector and sophisticated data analysis techniques, and development of an efficient alogorithm for computing interferometer performance for real interferometers.

Our interferometer consists of three equally spaced transmission diffraction gratings which function respectively much like the beam splitter, mirrors, and beam combiner in a diamond shaped Mach-Zender interferometer. This is a well known design whose general advantages have been eloquently extolled [CAL75], and which has been demonstrated with light, neutrons and x-rays. For atoms it can be realized either with matter (amplitude transmission) gratings or light (phase) gratings, but we elected to pursue the use of the more robust matter gratings. Our matter grating interferometer differs from most optical and neutron interferometers in that the interference is detected as a spatial variation of particle density at the third grating [CDK85]. This scheme requires only 2/3 the length of the usual far field detection method, giving us 3/2 greater separation of the beams in the interferometer for the fixed length of our beam tube.

The molecular beam apparatus used to house the interferometer is a modification of the apparatus used previously for our studies of light forces on atoms. The principal modifications were performed on the source and detector regions which were rebuilt. The effects of these modifications is apparent in the signals obtained from a single matter grating after modification.

Due to the sensitivity of atom interferometers to inertial effects such as acceleration and rotation, all types of mechanical vibration are of serious concern in this experiment. The relative transverse position of the three gratings must be known and controlled to within a fraction of a grating period over the measurement time. This requirement is 50nm rms motion over several minutes for our "standard" interferometer configuration with 200nm period gratings. A similar requirement limits the motion of the gratings due to acceleration of the center of mass of the grating system during the time it takes the atoms to traverse the interferometer, which is 1.3 ms. This means that the rms acceleration below ~ 900 Hz must be less than $10^{-2}\,ms^{-2}$. Finally, variations in the rotation rate during the traversal time should be well below 10^{-4} rad/s.

We went to great lengths to passively isolate the machine from building noise, and took specific steps to reduce mechanical noise from the various mechanical vacuum pumps. Two levels of flexible coupling were added to the rough vacuum lines, the mechanical pumps were moved several meters from the experiment, and our turbo pump was isolated using a vacuum bellows. This helped a great deal but left us a factor of two away from our goal. A more compliant suspension for the apparatus was ruled out because the interferometer is too sensitive to low frequency rotational noise.

We completed our vibration isolation with the active position servo system. The three atom diffraction gratings are mounted on separate translation stages in the vacuum envelope. The servo's position sensor was an optical interferometer whose diffraction gratings were mounted on the same translation stages used for the atom gratings. By running the optical interference signal through a feedback network and applying the correction signal to a piezoelectric transducer on one of the translation stages, the relative motion of the atom gratings can be reduced to ~ 40nm rms.

Several other advantages were gained from using this optical interferometer to measure the grating position. This servo loop gives excellent stability over the time we take data, and even between adjacent data sets. Another advantage is that we can vary the reference voltage (and therefore the reference position) of the servo loop to scan a grating controllably over the interference pattern. This is how we have taken all of our data.

In addition to the required position stability in inertial space, the three gratings must be aligned so that their grating lines are parallel to ~ 10^{-4} radians. To achieve this, we developed a system of alignment that relies on laser diffraction from the support structure of the gratings (the grating bars are too closely spaced to diffract a HeNe laser beam). This method also has the benefit of aligning the gratings in the earth's gravitational field, important because of the interferometer's sensitivity to gravitationally induced phase shifts.

Improved data analysis allowed us to demonstrate an excellent signal to noise ratio in our interferometer. We made improvements in our original data analysis techniques in both software and hardware. The hardware we are using is a Macintosh IIci computer. The software consists of a set of macros and external subroutines used in a commercial data analysis package named Igor. The macros import the data, deconvolve the position from the lock loop error signal and provide the interface to our external subroutines that we have written in C. The external subroutines remove noise bursts from our data, bin the count data into positional bins, and extract the phase and amplitude of the interferometer signal.

Because each grating/slit assembly in the interferometer is neither in the near field nor the far field of the others, it is not possible to produce an analytic expression for the interference signal [CLA91]. We have therefore undertaken a program to model the interferometer numerically. In doing so we have advanced the state of the art for these calculations by devising a way to cast the multiple grating problem as a convolution problem, enabling us to use Fast Fourier Transforms [TUR91, TPK91]. A ten minute run on a CRAY can simulate the interferometer with an incoherent source possessing the actual velocity profile. The ability to model our experiment not only enables us to predict the size of our signals and to optimize design changes to the interferometer, but also to plan experiments to study other atom optical effects (eg. Talbot fringes [JAL79, SUT79] in the intermediate field of a single grating). Numerical simulations have so far allowed us to investigate several important issues in interferometer design. We have investigated the rate at which fringe contrast degrades with mis-spacing of the three gratings and due to the spread of initial velocities (and corresponding change of deBroglie wavelengths) in the source beam. We have recently examined the possibilities of constructing interferometers with varying degrees of beam collimation, and we plan to study the effects of source coherence (the collimator does not really have a blackbody source behind it).

At MIT Submicron Structures Laboratory (SSL)

The key precursor to our successful program to build a three grating interferometer came from our demonstration [KSS88] that the 2000 Å period transmission gratings constructed for x-rays in the MIT Submicron Structures Laboratory could diffract atoms. We collaborated with M. Schattenberg in the SSL to produce gratings with higher transmission for atoms, but these gratings — although they gave excellent diffraction patterns — proved unsuitable for our interferometer due to previously undetected large scale irregularities. (Gratings for an interferometer must not deviate from a perfect grating by more than a small fraction of a period over the active area.) We then went to the National Nanofabrication Facility and learned to make gratings ourselves.

At National Nanofabrication Facility (NNF)

With the help of the staff (particularly M. Rooks), we used the facilities at NNF to develop procedures for making atom optics in thin (210 nm) silicon nitride membranes supported by conventional silicon wafers. We developed a new nanofabrication process for this — a special reactive ion etching gas mixture which etches Si_3N_4 faster than PMMA (plexiglass). This enables us to write a high resolution pattern in a thin overlayer of PMMA using an electron beam writer, chemically remove the exposed material, and then use the resulting pattern as a direct positive mask for etching the Si_3N_4 membrane, circumventing the need for making an intermediate metal mask as was previously necessary. This simplification increases the resolution and reliability of the fabrication process while shortening the cycle time, and may have other applications in nanotechnology. Although we made 2000 Å gratings which gave good diffraction patterns, the electron beam writer had some large scale pattern alignment problems which prevented their use in the interferometer — therefore we used our 4000 Å gratings to demonstrate the interferometer.

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