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FINAL REPORT

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"Atom Interferometry in a Microgravity Environment"

The scientific objectives for this proposal were: (i) development of a rugged laser cooled source of atoms using DBR/DFB laser technology; (ii) to use this source and these lasers to demonstrate coherent atom manipulation techniques; and (iii) to incorporate these techniques into atom interferometer inertial force sensors. Our fulfillment of these objectives is detailed below.

Gyroscope

We have demonstrated a Sagnac effect atom interferometer gyroscope that uses stimulated Raman transitions to coherently manipulate atomic wavepackets. We have used this gyroscope to measure the Earth's rotation rate, and have measured a short-term stability for rotations of 2×10^{-8} rad/sec/(Hz)$^{1/2}$ [1].

Our approach has been to use stimulated Raman transitions to coherently manipulate a transversely laser cooled atomic beam, as shown in Fig. 1. In this geometry approximately 10^7 atoms/sec contribute to the interference signal. We initially prepare atoms into the Cs F=3, $m_f = 0$ level, and subsequently subject the atoms to a three pulse sequence to divide, redirect and finally recombine atomic wavepackets. Interference is manifested through the number of atoms in the F=4, $m_f=0$ level after the three pulse sequence. The resulting Sagnac loop has an area of 25 mm^2. This corresponds to a fringe shift of ~8 rad for the Earth's rotation rate $\Omega_e = 7\times10^{-5}$ rad/sec. Our signal to noise was good enough to split the fringe by 1 part in 500 after 1 second of data collection time.

Our apparatus consists of a ~ 2 m long UHV vacuum chamber (base pressure ~5×10^{-10} torr) mounted just above a floating optical table. Care was taken to minimize vibrational coupling between the table and the chamber. The optical table contained the optics and laser system used for the wavepacket manipulation as well as for the laser cooling. In order to observe interference fringes the entire optical table was made to rotate by driving horizontal table rotational modes. This was done with a PZT, which was attached at one end to the floating table, and on the other end to an independent platform just next to the optical table. The induced rotation rate was independently measured with a seismometer located on the optical table. Fig. 2 shows the number of detected atoms in an 800 msec interval vs. the induced rotation rate. Note that the center of the fringe is

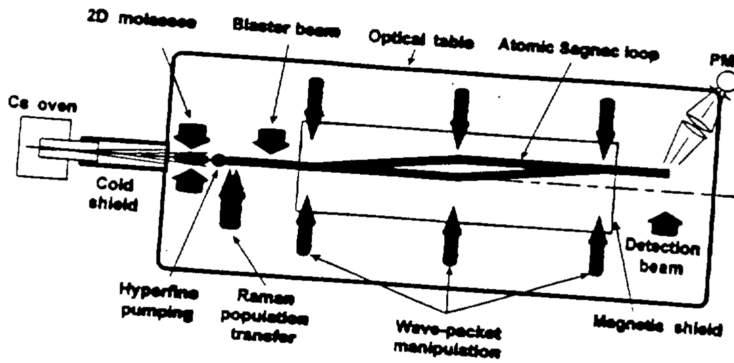

Fig. 1. Schematic illustration of the gyroscope apparatus.

offset from the zero rotation rate inferred from the seismometer. This offset arises because the seismometer is not sensitive to low frequency excitations such as those arising from the rotation of the Earth. The gyroscope, on the other hand, is. Accurate measurement of this offset allows for determination of the Earth's rotation rate.

We developed a new laser system to drive the stimulated Raman transitions needed for wavepacket manipulation [2]. This laser system was developed with the aim of creating a system which is robust and reliable enough so as not to limit the long-term stability of the gyroscope. Recall that the stimulated Raman method requires two high power laser beams which differ in frequency by 9.2 GHz, the cesium clock frequency. Our approach has been to derive these two beams from a master diode laser and a high frequency acousto-optic modulator, and then to amplify these two beams using optical injection locking techniques. A key issue is whether the amplification process introduces low frequency phase noise. By driving the Cs clock transition in the classic Ramsey configuration, we characterized the phase noise in the 1 - 100 Hz band, and demonstrated that these sources can be used for precision measurements.

Gravity Gradiometer

We have just recently demonstrated a proof-of-principle of the gravity gradiometer configuration discussed above. We have simultaneously measured the gravitational acceleration of two ensembles of laser cooled atoms separated vertically by approximately 1 m using a common set of Raman beams. Our near term goal is to demonstrate a sensitivity to gradients at the 10 E/Hz$^{1/2}$ level.

Approximately 10^8 atoms are initially captured from a dilute Cs vapor into a magneto-optic trap in each of the two UHV (base pressure ~ 1×10^{-9} torr) vacuum chambers. The vacuum chambers are manufactured from non-magnetic Al blocks, with high optical quality, anti-reflection coated, indium seal windows. Laser light for trapping and cooling is delivered to the chamber with optical fibers. After loading the traps, the quadrupole trapping fields are switched off, and the atoms are further cooled in an optical molasses. Following this cooling interval, the laser cooling light is switched off, and the atoms fall freely under the influence of gravity. A sequence of pulses is used to prepare the Cs atoms in the F=3, $m_f = 0$ groundstate. Atoms in this state are then subjected to the three-pulse interferometer sequence. The fraction of atoms driven to the F=4, m_f=0 state are detected using a normalizing resonance fluorescence technique.

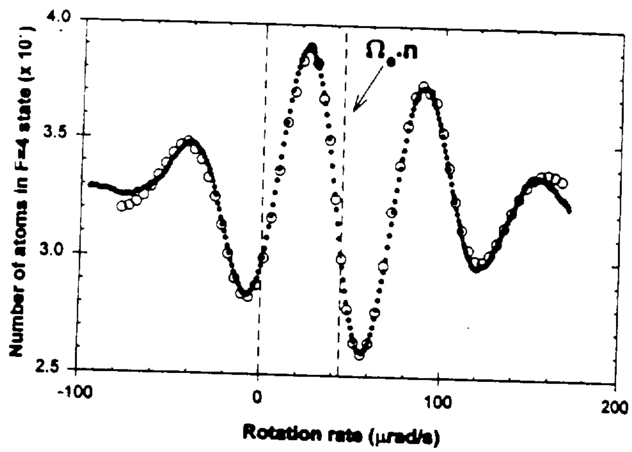

Fig. 2. Interference fringes vs. rotation rate for the atom interferometer gyroscope. The shift in the contrast envelope provides a measurement of the Earth's rotation rate.

We are using an all diode laser system similar to that developed for the gyroscope (described above). Unlike the gyroscope experiment, we need to dynamically control the relative frequencies of the Raman laser pulses. Using state-of-the-art direct digital synthesis techniques, we are able to rapidly, and phase continuously, switch the frequency and phase of the Raman laser pulses. Fig. 3 shows a scan of interference fringes recorded from both chambers simultaneously. These fringes were recorded with a low resolution T=10 msec time between pulses. In the near future we hope to extend this interrogation time to T= 50 msec, and are working on improvements which should increase the signal to noise by more than two orders of magnitude. If we are successful, our instrument sensitivity should be ~10 E/(Hz)$^{1/2}$.

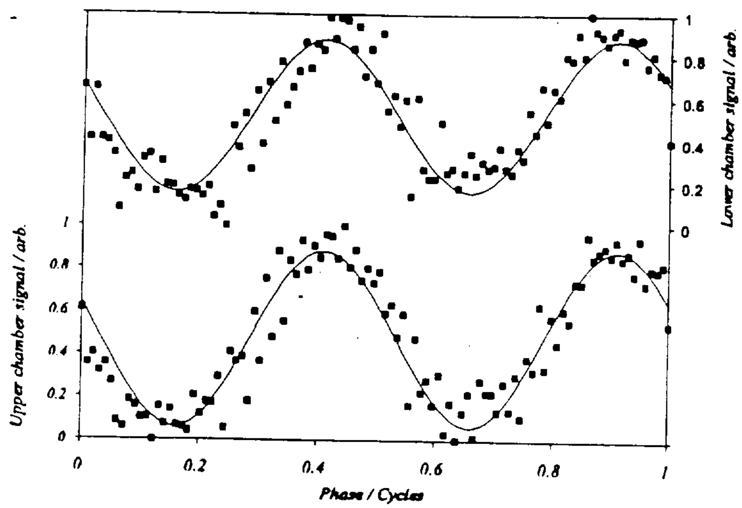

Fig. 3. Interference fringes obtained from the proof-of-principle gravity gradiometer experiment. The fringes were obtained simultaneously from two interferometers separated vertically by ~1 m. In this low-resolution mode, we do not expect a visible phase shift between the two traces.

References

1. Precision rotation measurements with an atom interferometer gyroscope, T. Gustavson, P. Bouyer, and M. Kasevich, Phys. Rev. Lett. **78**, 2046 (1997).
2. Microwave signal generation with optical injection locking, P. Bouyer, T. Gustavson, K. Haritos and M. Kasevich, Optics Letters **21**, 1502 (1996).