Point Source Atom Interferometer Gyroscope for Navigation and Precision Measurements

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Abstract: We characterize and extend the technique of point source atom interferometry (PSI) with cold atoms in a centimeter-scale vacuum cell. PSI uses optical Raman beams to create an atom optics interferometer with an expanding cloud of laser-cooled atoms. The measurement is inherently multi-axis, measuring the component of the rotation vector of the system in the plane perpendiuclar to the Raman beam axis and the acceleration along the Raman beams. For rotation, we measure the sensitivity to be $0.033\,^\circ/s$ for the rotation magnitude and 0.27° for the rotation direction, each for one second averaging time. Here we discuss ongoing work in improving the sensitivities, including measurement protocols and system design, while restricting the size of the instrument for use in inertial navigation.
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1. Introduction

Light pulse atom interferometry [1] enables inertial measurements of acceleration and rotation. Recent research includes building both larger more sensitive laboratory experiments [2–4] and on creating portable instruments for field work [5–8]. Our work explores the potential for a particular technique, point source atom interferometry (PSI) with cold atoms [9, 10], to be used in a compact quantum sensor [11, 12].

PSI has a number of inherent advantages over many other atom interferometer techniques, including multi-axis sensitivity, a non-ambiguous rotation measurement, and a simplified experimental apparatus. By using an expanding cloud of cold atoms with the Mach–Zehnder-like optical Raman pulse sequence, PSI generates spatial interference fringes in the atomic spin state (see Figure 1) [9–12]. Each atom interferes only with itself; this parallelism creates a phase gradient, and therefore fringes, across the cloud that depends on the inertial motion of the system. The symmetry of the light-atom interaction enables the measurement of the rotation vector in the plane perpendicular to the optical beam axis and the acceleration in the direction of the optical beam. The fringe orientation measures the rotation direction, the fringe frequency the rotation magnitude, and the fringe offset the acceleration (see Figure 2).

2. Measurements

The performance of our compact PSI-based instrument is limited by a number of effects such as the interrogation time of the optical Raman sequence, the atom cloud not being an ideal point source, the dead time of the experiment, the Raman laser phase noise (90 mrad at 1 s), the vibrations of the Raman optics (62 mrad at 1 s), and others [12]. In our current configuration, the measured sensitivity for the magnitude and direction of the applied rotation vector is 0.6 mrad/s and 5 mrad, respectively [12]. Our estimates of the shot-noise-limited performance for an ideal point source gyroscope with the same parameters are 2 rad/s and 50 rad at 1 s.

A compact system has intrinsic challenges that we are working to further understand and overcome. For example, in a compact setup with a fast repetition rate ($\sim 10\,\mathrm{Hz}$), the final cloud and initial cloud differ in size by a small factor (<2.5) and therefore our PSI gyroscope operates outside of the point source limit []. The scale factor, relating the measured to the actual rotation, is therefore modified such that $\Omega_{\mathrm{measured}} = \Omega_{\mathrm{actual}}(1-\sigma_0^2/\sigma_f^2)$, where σ_0 and σ_f are the initial and final cloud waists, respectively. Our recent roatation stability measurements indicate that the dominant source of noise is due to fluctuations in the initial cloud shape, size, atom number, and temperature. These fluctuations lead to fluctuations in the scale factor and therefore limit the sensitivity of our measurement. We are pursuing multiple approaches for mitigating, compensating for, and removing these effects. We have developed a new higher bandwidth and high dynamic range measurement technique [13] to support these efforts.

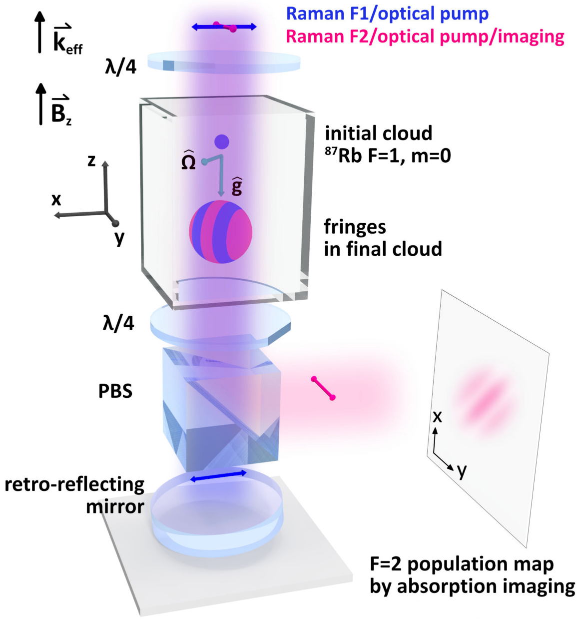

Fig. 1. Illustration of the compact point source atom interferometer physics package. The optical Raman beams are oriented anti-parallel along gravity (z-axis). A pizeo-driven retro-reflecting mirror below the cell enables simulation of rotations. Using absorption imaging, we detect spatial fringes in the atomic spin state distribution using a camera. The fringe orientation and frequency measure the direction and magnitude, respectively, of the applied rotation in the xy plane.

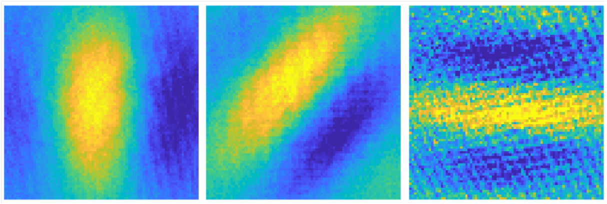

Fig. 2. Interference fringe data generated by simulated rotation. Left: $\Omega_y = 35$ mrad/s. Center: $\Omega_x = \Omega_y = 25$ mrad/s. Right: $\Omega_x = 89$ mrad/s.

3. Conclusion

Point source atom interferometry has potential for applications requiring a compact science package. We have measured the sensitivity of our apparatus and are further characterizing and optimizing the system and protocols within such goals.

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