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High Data-Rate Atom Interferometer Accelerometers and Gyroscopes

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Abstract

Light pulse atom interferometers have the potential to be exceptional broadband inertial sensors in both translational and rotational degrees of freedom. The demonstrated performance of this technology rivals the best ring-laser gyroscopes and falling corner-cube gravimeters. However, compact and field-worthy manifestations of atom interferometers remain elusive using standard approaches. Furthermore, with bandwidths currently limited to a few Hz, broadband seismic applications are yet to be realized. We propose to explore a short time-of-flight approach which we anticipate will reduce sensor size, improve ruggedness, and increase bandwidth by two orders of magnitude. This could lead to inertial sensors with applications in inertial navigation, mineral exploration, seismic monitoring, and national security.

Theory

Laser ranging of atoms in free fall

In light-pulse matterwave interferometers, the measurement can be approximated as laser ranging of atoms in free fall. Consider a conceptual model of an atom that acts as a memory device for the local phase value of a laser light field where

$$\phi_i = \vec{k}_{eff}\cdot\vec{x}_i. \quad (1)$$

Here, $|\mathbf{k}| = 4\pi/\lambda$ is the wavevector of the light field and x_i is the position of the atom along the direction of the light propagation. If the atom could be made to measure phase values at three, equi-spaced times T and then perform arithmetic on collected phase values according to

$$\Delta\phi = \phi_1 - 2\phi_2 + \phi_3 \quad (2)$$

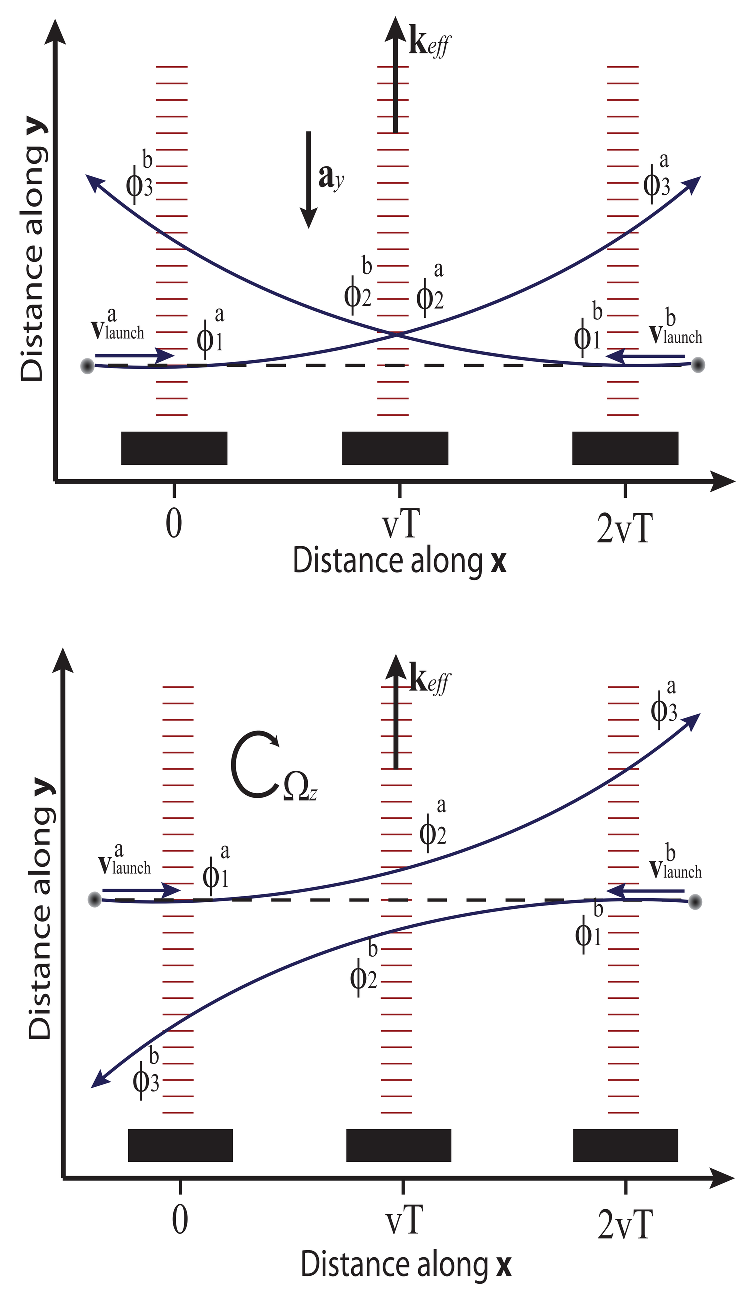

Figure 1. A conceptual model comparing two counter propagating atom trajectories under the influence of platform acceleration (top) and platform rotation (bottom).

then the acceleration of the atom with respect to the laser could be measured according to

$$g_x = \frac{\Delta\phi}{k_{eff}T^2}. \quad (3)$$

This model can be adapted to capture a rotation measurement as well [1]. If the atom has a component of an initial velocity ***v***, perpendicular with respect to the wavevector **k**, then a rotation of the lab frame about an axis along **k x *v*** appears as a parabolic trajectory along **k** (see figure 1). If two atoms counter-propagate along the same trajectory, then one can capture simultaneously a rotation measurement and an acceleration measurement. The Δϕ for each atom is then

$$\Delta\phi = \vec{k}_{eff}\cdot(\vec{a}T^2 - 2(\vec{v}\times\vec{\Omega})T^2). \quad (4)$$

Quantum mechanical approach

The measurement mechanics involve imprinting the optical phase of the laser onto the quantum mechanical phase of the atom's internal electronic state [1]. This can cause the atom's internal state to oscillate sinusoidally between the two hyperfine ground states.

Simultaneously, conservation of momentum demands that the field impart a two-photon recoil momentum kick to the population transferred to the excited state, causing the two states to separate far outside their coherence length. By varying the pulse duration of this coherent process, one can use the velocity recoil to create a matterwave beam splitter (π/2-pulse) and a mirror (π-pulse) from which to construct a π/2-π-π/2 Mach-Zehnder atom interferometer. Each interaction with the optical field imprints a phase onto the state of the atom according to

$$\left.\begin{array}{l} |1,\vec{p}\rangle \rightarrow e^{i\phi}|2,\vec{p}+\hbar\vec{k}_{eff}\rangle \\ |2,\vec{p}+\hbar\vec{k}_{eff}\rangle \rightarrow e^{-i\phi}|1,\vec{p}\rangle \\ \phi = \vec{k}_{eff}\cdot\vec{x}_i \end{array}\right\} \begin{array}{l}\Delta\phi = \phi_1 - 2\phi_2 + \phi_3 \\ = \vec{k}_{eff}\cdot(\vec{a}T^2 - 2(\vec{v}\times\vec{\Omega})T^2)\end{array} \quad (5)$$

Following the interferometer, the probability for an atom to be in atomic state |e> is P(|e>) = 1/2 (1-cosΔϕ) where Δϕ is defined above. This probability distribution can be measured with high fidelity using state-selective light-induced fluorescence [2].

Experiment

Accelerometer testing

We have devised and tested a short time-of-flight atom interferometer accelerometer using a drop and recapture protocol [3]. A proof-of-concept demonstration is shown in Figure 2.

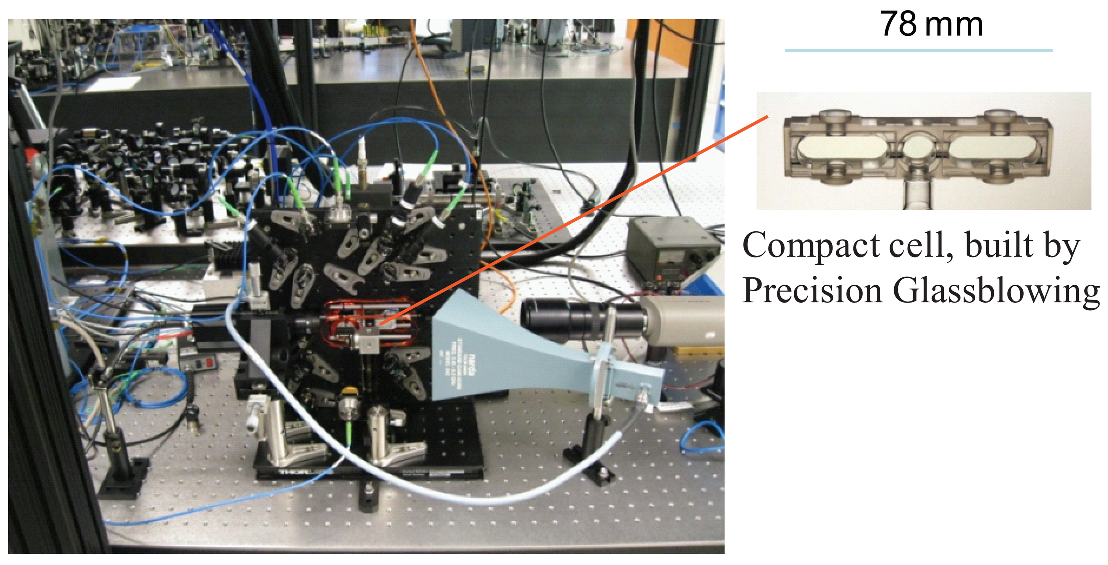

Figure 2. Short time-of-flight atom interferometer accelerometer using a compact vacuum cell.

Initial testing shows μg/rtHz level sensitivity at data rates of 50 to 330 Hz. Figure 3 shows the measured sensitivity versus data rate and the associated duty cycle achieved with this apparatus.

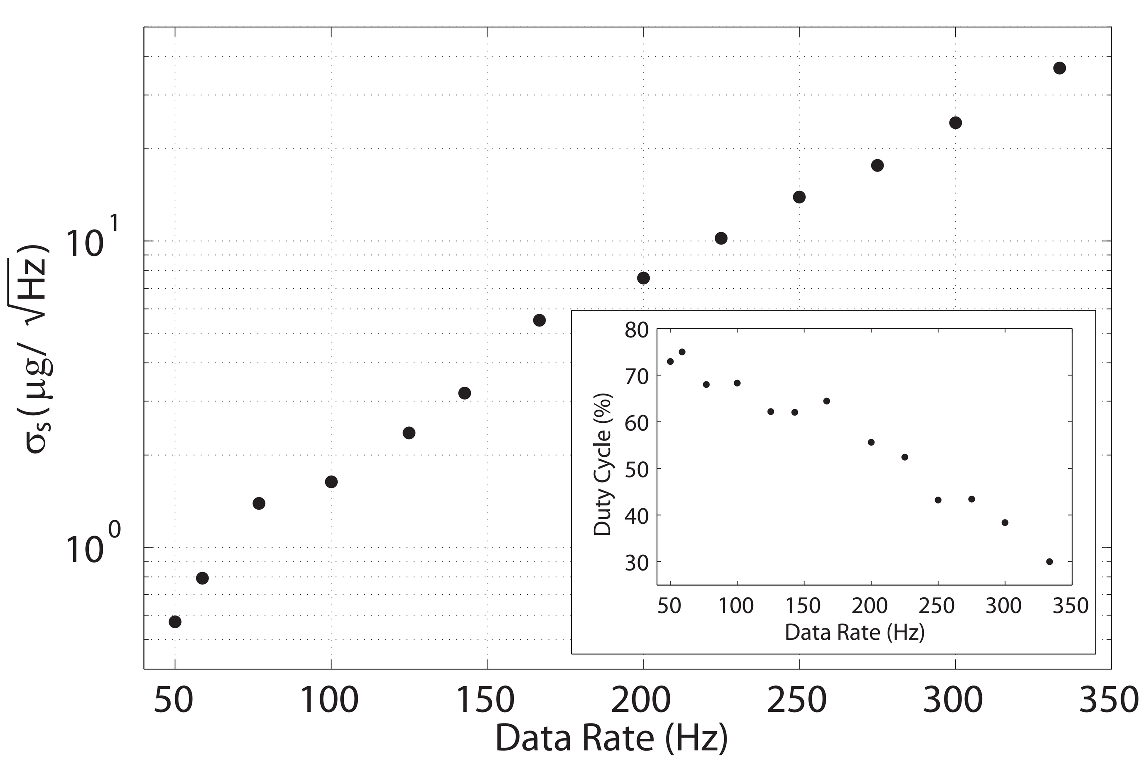

Figure 3. Plot of short-term sensitivity versus data rate, the inverse of the interferometer cycle time, from 50 Hz to 330 Hz. The inset plots the duty cycle versus data rate. The duty cycle was optimized for sensitivity.

Exchange-MOT interferometer

To implement simultaneous rotation and acceleration measurements in a short time-of-flight scenario, the conceptual configuration shown in Figure 4 could be used. Two atom clouds are launched from spatially separated magneto-optical trap (MOT) zones towards each other and interrogated with Raman pulses to measure acceleration and rotation. After the interferometer sequence, the atoms are recaptured for use in the next measurement cycle.

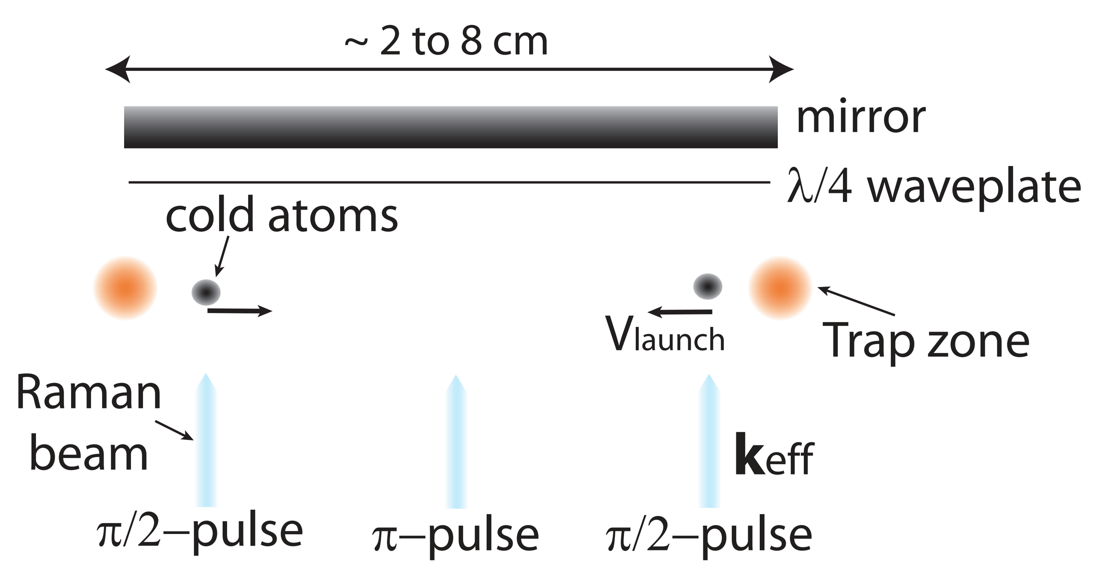

Figure 4. Functional configuration for a short time-of-flight, two axis sensor.

Figure 5 shows the experimental realization of the concept. The sensor head has a volume on the order of 1000 cubic centimeters. To date, acceleration and rotation sensitivities of 5.5 μg/rtHz and 2.9 μrad/s/rtHz, respectively, have been achieved at a data rate of 50 Hz.

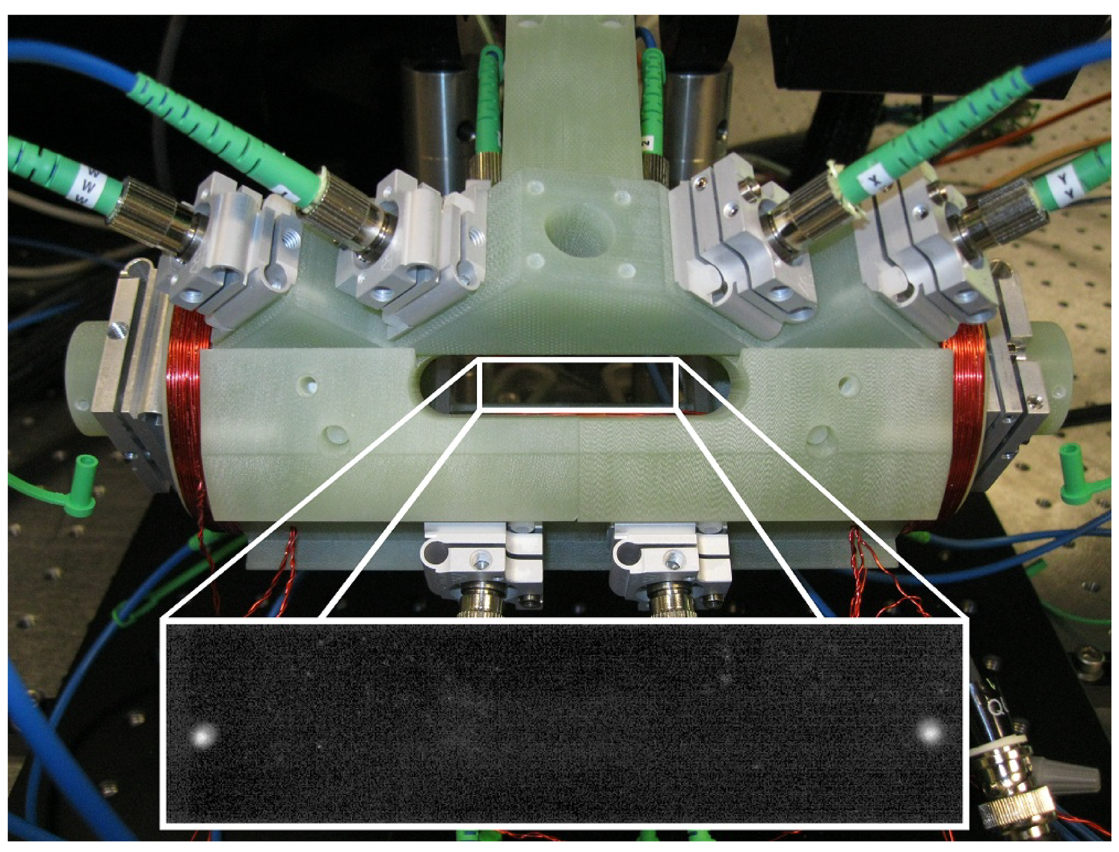

Figure 5. Realization of the exchange-MOT atom interferometer concept. The inset shows the two interferometer clouds directly before launch.

Figure 6 shows an experimentally obtained phase scan for both interferometer clouds. As the offset of Δϕ, related in equation (5), is changed by imparting a relative phase to one of the Raman beams, the probability that an atom will be in the excited state *F=2* varies in a sinusoidal manner.

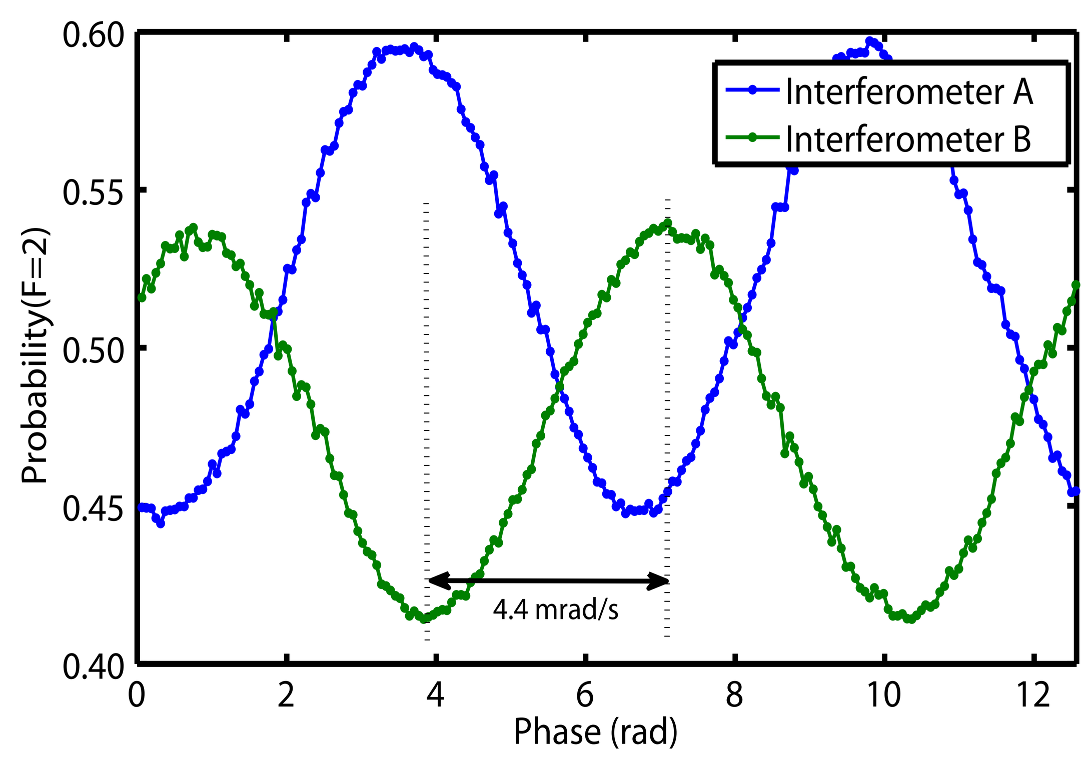

Figure 6. Phase scan for both interferometer clouds showing the sinusoidal variation in the excited state probability as a function of relative Raman beam phase. One fringe corresponds to a rotation of 8.8 mrad/s and an acceleration of 7.2 mg. The interrogation time was 2.372 ms.

References

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[2] G. W. Biedermann, X. Wu, L. Deslauriers, K. Takase, and M. A. Kasevich. *Low-noise simultaneous fluorescence detection of two atomic states*, Optics Letters, Vol. 34, p. 347. (2009)

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Acknowledgements

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