Navigation with Atom Interferometers

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Abstract: *In this article, we review the basic physics of an atom interferometer. We highlight the usefulness of atom interferometers for inertial navigation due to their high phase sensitivity to both linear acceleration and angular rotation, but also the drawback that a single atom interferometer cannot distinguish between the two sources of phase shifts. We describe a design for a dual atom interferometer to simultaneously measure acceleration and rotation and we describe the current status of our apparatus.*

Keywords: atom interferometers; inertial navigation; accelerometers; gyroscopes.

Introduction

The years 1991-1992 saw the introduction of four novel atom interferometers. [1-4]. Two of these [3, 4] investigated rotational sensitivity and the measurement of local gravity. Since then, an entire field of study has emerged, investigating the use of atom interferometers as inertial sensors.

The major promise of these devices is their inherent sensitivity which scales as the mass of the atom (or these days, molecules). Comparing an atom interferometer to an otherwise equal optical interferometer whose effective mass is given by the frequency of the light, an atom interferometer can be as much as 11 orders of magnitude more sensitive than the optical one [5]. Of course, there are some factors that make atom interferometers and optical interferometers otherwise not equal, including flux of the interfering particles and the ability of optical photons to be recycled. Still, atom interferometers can be 3-4 orders of magnitude more sensitive than optical interferometers. In addition to sensitivity, atom interferometers are based on the well-defined and uniform characteristics of atoms leading to excellent bias and scale factor stability.

This paper is organized as follows: we first describe the basic building blocks of the interferometer: beam splitters and mirrors. We then outline how these building blocks can be used in an interferometer configuration and we show how the phase of the interferometer can be derived. We describe our embodiment of a sensor that can give both acceleration and rotation information based on opposing atomic beams. We postulate the sensitivity of our device and provide a status of the current experiments. Finally, we conclude.

Physics of an atom interferometer

Basic building blocks: beam splitters and mirrors. The physics of an atom interferometer is very analogous to a Mach-Zehnder optical interferometer, with the roles of light and matter interchanged. An atom beam splitter splits the path on which an atom travels. Two mirrors then redirect the atom's path back towards itself and a final beam splitter recombines the two arms. The number of atoms at the output port is measured and oscillations can be observed when the timing between the atom optics is varied. The phase of these oscillations shifts when the device is rotated or accelerated.

In order to describe the atom optics, we consider a simple two level atom with two electronic states labeled |g> and |e> of energy spacing $\hbar\omega_o$, driven by a laser of frequency ω_L. This problem can be found in many standard quantum optics textbooks e.g [6]. In textbooks, the two states are usually ground and excited electronic states. However, electronic states usually spontaneously decay very quickly, spoiling the coherence required for the interferometer. In atom interferometer realizations, the two states are typically two ground states separated by an energy whose associated frequency is in the radio frequency part of the spectrum and the driving laser is made up of two laser frequencies whose frequency separation is close to the ground state frequency difference. For simplicity, the discussion below assumes two electronic states and one laser frequency. Even so, the physics of the driven ground state atom is the same as the driven electronic state problem.

When the atom is initially prepared in the ground state and then illuminated by a laser of frequency ω_L and electric field amplitude ε, the probability $P_e(t)$ of finding the atom in the excited state is given by

$$P_e(t) = \frac{1}{2}\frac{\Omega}{\Omega_g}[1-\cos(\Omega_g t)], \tag{1}$$

where $\Omega = \frac{2\mu\varepsilon}{\hbar}$ is the zero detuning Rabi frequency, μ is the atomic dipole moment, $\Omega_g = \sqrt{\Omega^2+\delta^2}$ is the generalized Rabi frequency and $\delta = \omega_L - \omega_o$ is the detuning of the laser from the atomic transition.

Equation (1) is plotted in Figure 1 for the parameter values listed in the caption. Its interpretation is simple: in the absence of any spontaneous emission or other decoherence mechanisms (which were ignored in the derivation of Equation (1)), the atomic population oscillates smoothly between the two states. For times satisfying $\Omega_g t = \pi$ (the so called 'pi-pulse'), the atom fully transfers from the ground state to the excited state (or, if it were initially in the excited state, it would fully transfer to the ground state). The key to realizing the interferometer is the fact that the change in electronic state is accompanied by a change in momentum. The ground state receives a "kick" of $\hbar k$, where k is the laser wavenumber in the direction of the drive laser. When the atom is in the excited state, the stimulated emission of the photon results in a momentum kick opposite to the direction of the driving laser. This type of pulse is a called an "atom mirror".

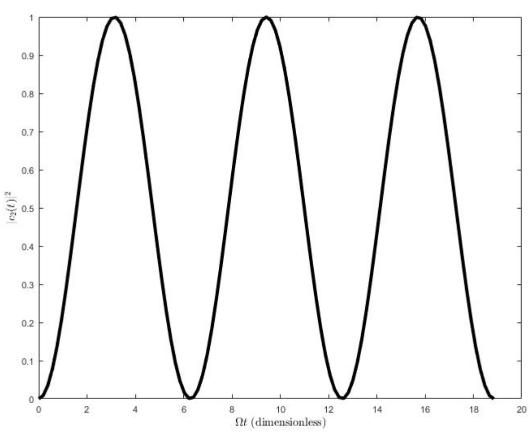

Figure 1: Plot of the probability of the atom being in the excited state as a function of scaled time Ωt for $\delta = 0$.

For times satisfying $\Omega_g t = \pi / 2$ (the so called 'pi/2-pulse'), the atom is in a coherent superposition of ground and excited states. The portion of the atomic wave function that corresponds to the excited state receives a momentum kick as described above, while the portion remaining in the ground state does not. The two states of the atom actually realize spatial separation. The action of this pulse is analogous to the action of a glass plate on an optical beam and therefore is called an "atom beam splitter". Present day interferometers have been demonstrated to have extremely large separations [7].

The action of the so called π–π/2–π pulse sequence making up a basic interferometer is depicted in Figure (2). A π/2 pulse is applied to atoms prepared in the ground state and initially traveling with some velocity v. After the pulse, the atoms are allowed to evolve "in the dark" for a period of time, denoted by T, and then encounter a π pulse. After a second free evolution period (of time T), the atoms are subjected to a final π/2 pulse. The number of atoms in the excited state are read out with a detecting laser. As illustrated in the next section, the probability of finding atoms in the excited state is interferometrically sensitive to the free evolution time T, which ultimately leads to inertial sensitivity.

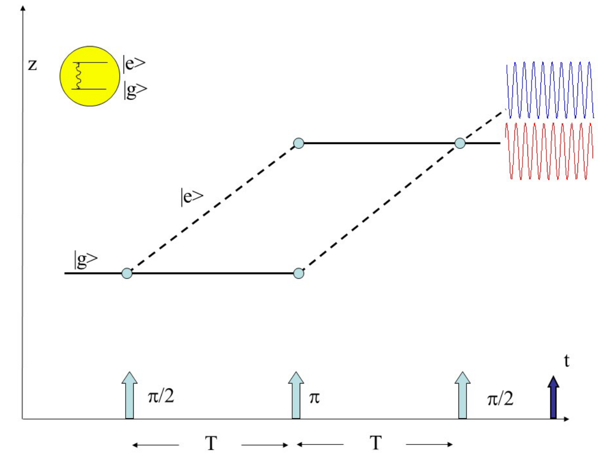

Figure 2: Depiction of the action of a standard $\pi / 2 - \pi - \pi / 2$ pulse sequence on a stream of atoms (after [8, 9]).

Phase of the interferometer: For illustrative purposes, we will consider atoms moving in a gravitational potential. There is a similar treatment for atoms on a rotating frame, whose result we merely quote at the end of this section. By the nature of the interferometer, the atoms moving through the interferometer are treated like waves and they acquire a phase given by [8, 9]

$$\hbar\phi = \int_{path} dt\, L(t), \qquad (2)$$

where L(t) is the Lagrangian given by the difference of the kinetic $K(t) = \frac{1}{2} m[v(t)]^2$ and potential $U(t) = mgz(t)$ energies L(t)=K-U integrated over the path followed by the atoms. The action of the first beam splitter causes the atoms to follow two different trajectories, which must be handled separately. The action of the last beam splitter is essentially to take the difference of the phases acquired in each arm. The trajectories need to include the fact that the laser pulses cause momentum kicks as described in the previous sub-section, which in the simplest form can be considered as instantaneous velocity changes. Although not especially difficult, the calculations can be tedious and finally result in the phase difference between the two trajectories being given by:

$$\Delta\phi \equiv \phi_2 - \phi_1 = 0, \qquad (3)$$

which is to say that the phase difference due to the motion along the classical path is zero.

However, there is a second contribution to the phase of the interferometer. If we assume the laser pulse duration is much shorter than the free evolution time, then the phase of the laser at the time of the pulse at the location of the atom is "imprinted" on the atom. Taking into account all three laser pulses, the phase difference then becomes

$$\Delta\phi = \phi(t=0) - 2\phi(t=T) - \phi(t=2T), \tag{4a}$$

which, when referenced to a fixed point becomes

$$\Delta\phi = -kgT^2. \tag{5}$$

The action of the laser pulses effectively takes a "picture" of the atoms' location at three positions using the laser's wavelength as the "ruler", from which the acceleration due to gravity can be extracted.

An analogous argument can be followed for an atom moving on a platform rotating with angular velocity W. In that case (and in the absence of linear motion), the phase difference is given by

$$\Delta\phi = \frac{2m}{\hbar}\mathbf{W}\cdot\mathbf{A} \quad , \tag{6}$$

where **W** is the rotation vector and **A** is the area vector.

Dual atom interferometer concept

Prior work: As developed in the previous section, atom interferometers have extreme sensitivity to both the rotation and acceleration of a platform. When a sensor using an atom interferometer experiences linear acceleration, a phase shift can be read-out from the interferometer and equation (5) can be used to calculate the acceleration. Similarly, when the platform is rotated, equation (6) can be used to infer the rotation. However, most platforms very rarely experience perfectly linear or perfectly rotational motion: usually, the platform trajectory is a combination of both types of motion. It is impossible for a single atom interferometer to distinguish between the two types of phase shifts.

While a single interferometer cannot yield useful information about either linear or rotational motion, a dual interferometer using opposing atom beams can provide information about both types of motion. Such an interferometer is depicted in Figure (3), which utilizes two atomic sources and common atom optics. The phase shift observed in one interferometer e.g. the interferometer comprised of atoms moving left to right, is given by the sum of equations (5) and (6).

$$\Delta\phi_{LR} = -kgT^2 + \frac{2m}{\hbar}WA \tag{7}$$

We note that the phase difference given by equation (6) depends on the dot product of the rotational vector with the area vector of the interferometer, which acquires a minus sign when the area vector flips. Therefore, the phase shift measured by the atoms moving from right to left is given by

$$\Delta\phi_{RL} = -kgT^2 - \frac{2m}{\hbar}WA. \tag{8}$$

By measuring the phase shift in both interferometers simultaneously, the acceleration can be extracted by adding the shifts and the rotation can be extracted by taking the difference of the phase shifts. A dual accelerometer/gyroscope based on opposing flying atom clouds has already been demonstrated in [10, 11].

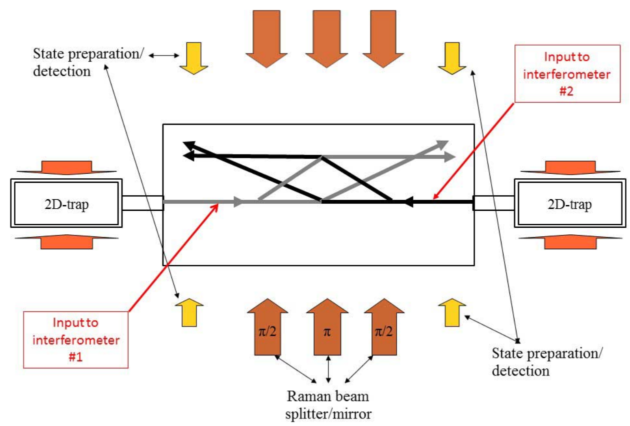

Figure 3: Depiction of our dual accelerometer/gyroscope based on opposing atomic beams.

Our design: Previous works [10, 11] suffer from two drawbacks that our design seeks to circumvent. The first drawback is that the system is pulsed. Atoms are caught in a 3-dimensional atom trap and launched towards each other. The clouds of atoms experience the π and π/2 pulses as the light beams are flashed on and the timing depends on the launch velocity of the two clouds. The 3-dimensional trap is loaded from an atomic beam emerging from a 2-dimensional trap. The 2D trap is used solely for the rapid loading of the 3D trap (20 milliseconds in the case of [11]). The other drawback of this design is the complexity and power requirements, especially for the 3-dimensional traps. Laser beams need to be turned on and impinge on atoms from six sides. Furthermore, the ability to pulse all the lasers at the appropriate times requires the use of acousto-optic modulators, which can require up to a watt of radio-frequency power per modulator. The timing sequence is connected to the launch velocity of the atoms.

Our design eliminates the use of the 3-dimensional trap entirely, therefore greatly reducing the complexity of apparatus (compare our figure (3) to figure (1) of [11]). It also eliminates the need to use modulators on the trapping beams, reducing the power requirements. Our design also uses 2 two-dimensional atom traps, but as a sources of slow moving atoms that are quasi-mono-energetic. Our atom optics beams are left on continuously (further eliminating modulators on the atom optics lasers) and we rely on the transit time of the atoms through the laser beams to form the atom optics "pulses".

Sensitivity

The sensitivity of an atom interferometer can be characterized by several parameters. For a gyroscope, these parameters are usually the angle random walk of the device and the bias stability. Bias stability is a function of the stability of the design and will be measured at a future time. Angle random walk can be calculated from first principles from the shot-noise limited fluctuations in the rotation signal. The phase fluctuations, denoted by $\Delta\phi$, are given by [12]

$$\Delta\phi = \frac{1}{C}\sqrt{\frac{1}{n_o\tau}(1+\frac{n_b}{n_o})}\,, \qquad (9)$$

where C is the (measured) contrast and $n_o\,(n_b)$ is the total (background) atom flux and τ is the sampling time. In deriving Eq. (9), we assume that we maintain a lock on the side of a fringe. Otherwise, the fluctuations would be $\sqrt{2}$ larger. The fluctuations in the rotation signal (denoted by ΔW) from Equation (6) is then

$$\Delta W = \frac{\hbar}{2mA}\frac{1}{C}\sqrt{\frac{1}{n_o\tau}\left(1+\frac{n_b}{n_o}\right)}\,. \qquad (10)$$

Similarly, the fluctuations in the acceleration signal Δa can be derived from Equation (5) and (9) and are given by

$$\Delta a = \frac{\lambda}{2\pi T^2}\frac{1}{C}\sqrt{\frac{1}{n_o\tau}\left(1+\frac{n_b}{n_o}\right)}\,. \qquad (11)$$

Our design goals are to demonstrate of $2x10^{-4}$ $degrees/\sqrt{hr}$ angle random walk and $3x10^{-4}$ $meters/second/\sqrt{hr}$ velocity random walk. These sensitivities require a flux of at least $2x10^{7}$ $atoms/second$, which we have demonstrated.

Current status

To date, we have constructed an apparatus and demonstrated most of the ingredients discussed in this article. Specifically, we have demonstrated:

- An apparatus with two opposing atom beams, each of which has a flux of approximately 10^9 $atoms/second$ which is two orders of magnitude larger than required.
- The ability to drive Raman resonances (which are the resonances described in the Physics of An Atom Interferometer section). This is shown in figure (4), where we scan the driving laser's frequency over the so-called "clock" transition and the first (positive and negative) magnetic Raman transitions.

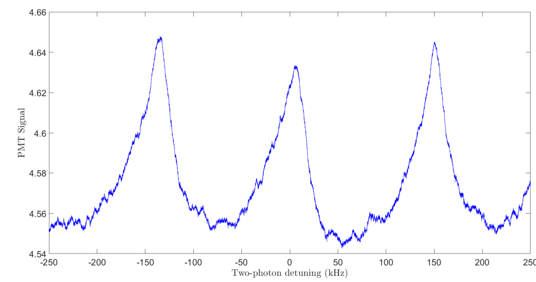

Figure 4: Measured Spectrum of resonances useful for the atom gyroscope/accelerometer.

Conclusions

In conclusion, in this article, we have reviewed the basic theory leading to the working of an atom interferometer and how an atom interferometer can be used as an accelerometer and a gyroscope. We discussed using opposing atomic beams to be able to simultaneously measure acceleration and rotation. We then compared and contrasted our design with state of the art dual accelerometer/gyroscope designs. We presented our design goals for sensitivity and finally presented the current status of the apparatus.

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