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Advances in Dynamic Range and Coherence of Continuous Cold-Atom Interferometers

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NRL has recently developed a unique capability of continuous, 3D-cooled atomic beam interferometry. Atom interferometers have historically suffered from low dynamic range as compared to classical sensors. Additionally, difficulties arise with maintaining coherence in the interferometric process when performing continuous, cold-atom interferometry. Here we employ our new atom interferometer architecture to address the issue of low dynamic range by ramping the velocity of a continuous atomic beam in order to infer the unambiguous absolute phase of an atom interferometer. Additionally, we will discuss techniques to characterize and improve on the coherence in our continuous, cold-atom interferometer.

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EXECUTIVE SUMMARY

NRL has recently developed a unique capability of continuous, 3D-cooled atomic beam interferometry. Atom interferometers have historically suffered from low dynamic range as compared to classical sensors. Additionally, difficulties arise with maintaining coherence in the interferometric process when performing continuous, cold-atom interferometry. Here we employ our new atom interferometer architecture to address the issue of low dynamic range by ramping the velocity of a continuous atomic beam in order to infer the unambiguous absolute phase of an atom interferometer. Additionally, we will discuss techniques to characterize and improve on the coherence in our continuous, cold-atom interferometer.

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ADVANCES IN DYNAMIC RANGE AND COHERENCE OF CONTINUOUS COLD-ATOM INTERFEROMETERS

1. INTRODUCTION

Generally, interferometers operate under the goal of precisely measuring extremely small variations in a quantity by inferring a measurement quantity from the interference of two waves. For example, a Michelson interferometer [1] involves sending waves along two paths to then be recombined and measured. The resulting interference from the two waves will indicate the relative length between the two interferometers, with a periodicity related to the wavelength of the wave. In another example, a Sagnac loop [2] involves sending waves along two different directions of a loop. A change in phase resulting from a path length difference in this scenario implies that some rotation must have occurred during the propagation of the wave. Many interferometers tasked to measure position or rotational interferometry signals have been demonstrated and proven with light, such as laser ring gyroscopes [3] or white light interferometers. If we instead utilize the atomic wavefunction to perform interferometry, we realize a fundamental advantage due to the extremely short atomic wavelength, though this is partially offset by practical constraints of interferometer design.

The advent of atom interferometry thirty years ago [4-8] has led to a number of laboratory experiments, precisely and accurately measuring quantities like accelerations, rotations, and gravity gradients. Initial experimental implementations of inertially sensitive atomic interferometers were done with a hot, continuous beam of atoms [9]. Operating continuously has the advantage of eliminating dead-time in the measurement, as well as reducing systematic errors. However, using hot atoms comes at the cost of reduced sensitivity. If cold atoms are used instead, more of the ensemble participate in the interferometer which in turn increases the sensitivity. Additionally, using cold atoms reduces some errors caused by coupling of motion to the atomic velocity distribution. However, cooling the atoms generates a lot of near-resonance light, which can decohere the interferometer [10-12].

Historically, many techniques have been used to decrease near-resonant light-induced decoherence, including pulsing the experiment and performing interferometry while the cooling light is off, using a parabolic trajectory [13,14], or interleaving periodic measurements in physically separate locations [15,16]. The method used in this study utilizes a bend in the atomic trajectory and cleverly situated mirrors in order to block any near-resonance scattered light from the interferometry region. This not only allows continuous operation, but does not require a stationary and specific atomic trajectory to mitigate fluorescence. This means that the method used here is much more robust against dynamics, and is theoretically orientation-independent. Additionally, pulsing the measurement introduces dead time which can lead to significant instability in an inertial measurement, or additional aliased errors in non-inertial measurements.

In principle, atom interferometry presents an immense improvement to state-of-the-art inertial sensors with some specific drawbacks. One of the most notable advantages is that the long-term drift of atomic sensors is much better than classical devices, though atomic sensors also generally have the advantage of reduced systematic error and better sensitivity. However, despite their advantages, atom interferometers have not replaced conventional sensors for high-sensitivity or low-drift applications. There are a number of reasons for this, including size requirements and low dynamic range.

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The dynamic range of a sensor can become problematic if the sensor is operating under dynamics, and the interferometer undergoes more than one phase wrap within a measurement cycle. If an atom interferometer has any hope of operating on a fieldable platform under dynamics, either a co-sensor must be used or techniques must be developed to address the dynamic-range deficiency. Co-sensor implementation can be tricky and introduce additional errors into the system. For example, cosensor alignment, bias drift, scale factor drift, and scale factor nonlinearity must all be precisely estimated for effective cosensor fusion to increase dynamic range. Additionally, in noncontinuous applications the short-term noise of the cosensor becomes dominant, eliminating much of the advantage of using atom interferometers.

On the other hand, the extension of dynamic range in atom interferometers is a current research topic for a number of groups. The prevailing research on this front uses a pulsed interferometer, and is able to observe a ~10 times improvement with a measurement period of ~2 seconds [17]. They are able to modify their experiment to observe a $\sim 10^2$ dynamic range improvement, but at the cost of bandwidth, with a measurement period of 10 seconds. Here, I will present a similar methodology to extend the dynamic range of our continuous interferometer by a factor of 100 over a measurement cycle of ~0.5 seconds. However, it is worth noting that the 100x improvement in dynamic range was limited by the test platform and not the measurement itself. In principle, the method used here to measure dynamic range could be extended to measure any static acceleration that preserves interferometer fringe contrast.

2. APPARATUS

The atom interferometer consists of an atom source as well as an interferometry chamber. Details of our apparatus can be found in the published literature [18,19], but we will briefly present an overview here for completeness. The atom beam is first generated from a cell with a rubidium source where we implement two-dimensional magneto-optic cooling. In magneto-optic cooling a laser beam is tuned slightly off-resonance and retro-reflected which creates an optical molasses. A magnetic field is applied to produce a spatial variation in the optical force, and in this case causes atoms to collect in a line along the longitudinal direction of the cell. These atoms are transversely cooled and longitudinally warm, and referred to as a two-dimensional magneto-optical trap (2D MOT). The atoms then travel through a pinhole into a secondary cooling stage at a slight angle from the first. In this cell, the atoms are further cooled in a three dimensional moving molasses into a moving frame of reference. The atoms are redirected to separate the atoms from the propagation of light from the 2D MOT stage.

The atom beam travels into a long chamber in which we perform atomic interferometry. The atoms are first optically pumped into a single ground state, and are then coherently transferred between the two rubidium ground-states via a two-photon Raman transition. These transitions between ground states can be configured to impart momentum to the atoms, which allows for coherent splitting between momentum states. In this case, we use three Doppler-sensitive Raman pulses applied nearly transversely (at a slight angle from normal) to the atoms to coherently split, mirror, and then recombine the atoms in a rotation- and acceleration-sensitive interferometer loop. The Raman beams are situated at an angle in order to use

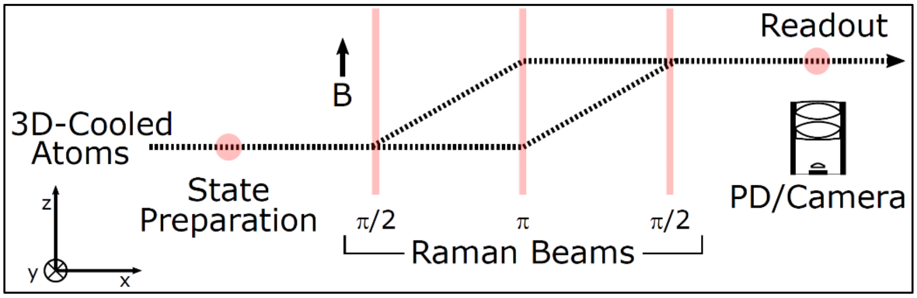

Figure 1: The 3D-cooled atom beam travels through a state-preparation region, and then passes through an interferometer region consisting of three Raman beams, followed by readout with a photodiode or camera. The Raman beams are actually slightly offset from the z-axis, by approximately 0.5 degrees. In this orientation, the interferometer is sensitive to rotations about the y-axis and accelerations along the z-axis.

the Doppler shift to differentiate between the two-photon resonances, which in turn allows us to determine in which direction momentum is imparted on the atoms. This configuration can be seen in Fig. 1.

The configuration of the atomic cooling allows some flexibility of the atomic velocity entering the interferometer region. The reference frame into which the moving-molasses cools can be modified by the frequency of light applied in the cooling region. The fraction of atoms cooled into the moving frame is determined by the atoms entering the cooling region, and thus we have flexibility to modulate the atomic velocity anywhere between 6 m/s and 16 m/s. For the purposes of this experiment, we choose to operate nominally at 11 m/s. When operated in velocity-ramp mode, the velocity is nominally 11 m/s with a 100 ms ramp of +/- 0.1 m/s.

To correct for certain systematic errors, we periodically reverse the direction of momentum imparted to the atoms in a method known as case-switching or in this scenario, k-switching. This is done by tuning the two-photon detuning of the Raman beams between the positive and negative two-photon resonances. k-switching has been demonstrated in the current system at switching-rates of up to 9/T, or ~1.5 kHz. In this study, we choose not to switch k within the interrogation time for simplicity, and results are shown at k-switching rates of ~2 Hz. Fast k-switching rates are only required when platform dynamics are introduced, and all measurements here were effectively static.

3. DYNAMIC RANGE IMPROVEMENT

The atom interferometer used in this study consists of a continuous, cold atomic beam designed to mitigate scattered-light induced decoherence, as described in the previous section [18,19]. While typical atom interferometers operate with discrete measurement cycles, the atom source presented enables continuous operation which mitigates aliased noise and eliminates dead-time between measurements. Cooling the atoms in three dimensions enables more atoms to participate in the interferometer sequence, while also reducing the effect of dynamics on the interferometer operation. Like many interferometers,

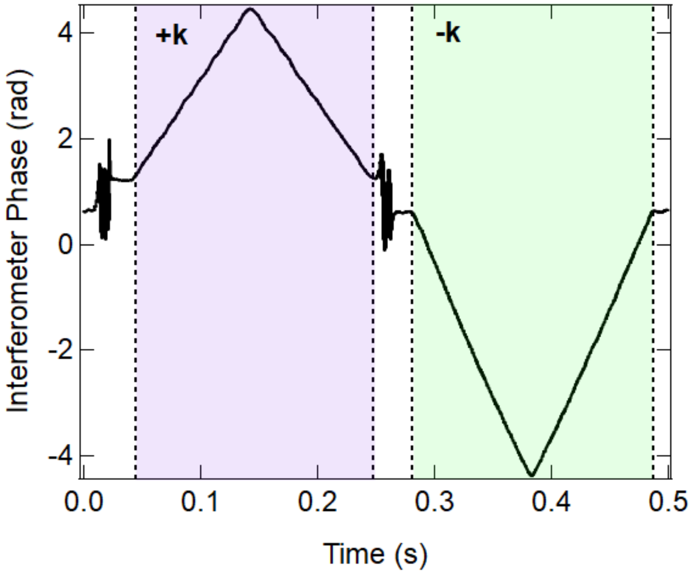

Figure 2: The interferometer output is shown for each stage of the atomic velocity ramp. The velocity ramps +/- 0.1 m/s from a nominal 11 m/s over 200 m/s, and the process is repeated for each direction of k. The slopes can be fit and determine a total phase measurement of 105 radians.

the one demonstrated here suffers from a limited dynamic range. We address this limited dynamic range by rapidly switching the velocity of the atomic beam in the interferometer.

In their method to address the limited dynamic range of an accelerometer, Yankelev *et al.* [17] operated their interferometer at two different interrogation times T_1 and T_2, where in general T is the length of time between two pulses. The dynamic range increase of the sensor is $D = (1 - \tau)^{-1}$, with $\tau = (T_2/T_1)^2$. Thus, a larger dynamic increase is obtained from small changes in velocity. This process is limited by the noise of the interference measurement, and how well the phases from two different interrogation times can be distinguished. In their study, Yankelev *et al.* used two and sometimes three different values of τ taking up to 10 seconds to perform a measurement for the latter. Here, we instead continuously vary the velocity of our atom beam. In the configuration used here, the velocity determines the traversal time of the atoms through the interferometer, and hence the interrogation time.

A fit to the slope of the resulting interferometer phase can be used to extract the absolute phase from the interferometer. Then, k-reversal will help to isolate what portion of this phase is due to an inertial signal. The largest inertial phase measured is 105 radians, corresponding to an acceleration of 0.15 m/s or a 0.1 degree tilt of the interferometer. This measurement is shown in Fig. 2. The absolute phase measurement is not fundamentally limited at the 105 radians measured here. The measurement was repeated for a number of smaller angles and subsequently verified with the use of an autocollimator and tilt sensor.

The measurements taken here were limited by the experimental apparatus, as it was installed on a fixed optical table. The 0.1 degree tilt represented the maximum tilt allowed by the fixed stage. Theoretically, this measurement technique could be used to measure any static absolute phase of the interferometer as long as there is fringe contrast in the interferometer. The current method could also be extended to a dynamic phase measurement, as long as the time variation is << 1 Hz. Further improvements could be made by performing sub-interrogation time k-reversal, which would substantially increase the bandwidth of the measurement.

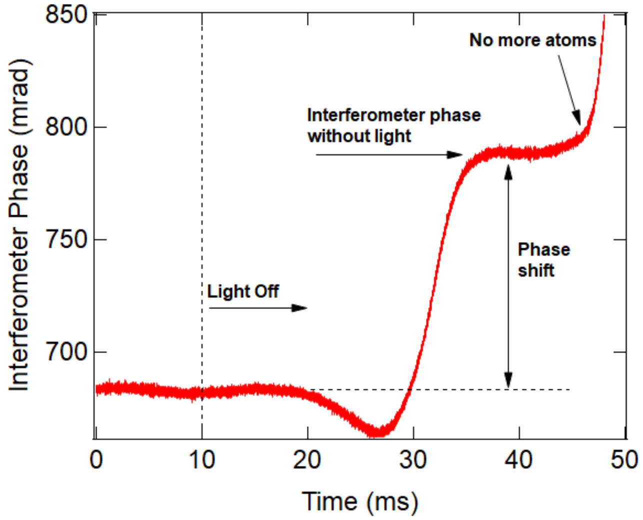

Figure 3: The interferometer phase can be monitored to determine the phase induced by light. The light is turned off at 10 ms. Approximately 10 ms later, the atoms that were in the beginning of the interferometer at the time of turn-off enter the detection region. The final plateau at 40 ms shows the interferometer phase with the selected light source off, from which a phase shift can be measured.

4. PHASE ERROR

Another topic addressed in this program was assessing and improving the phase error in the continuous atom interferometer, specifically due to scattered near-resonant light. Because the cooling light is on continuously, there is a possibility that any light from the cooling region could enter the interferometry region and cause the interferometer to decohere. Additionally, this near-resonance and on-resonance light will cause phase shifts in the interferometer. This phase shift was quantified by pulsing each light source in the experiment, and tracking the phase of the interferometer throughout. For light in the chambers preceding the interferometer region, turning off the light would lead to a brief drop, and then increase in the phase to a plateau, before the atomic signal was completely lost. This can be seen in Fig. 3.

An analysis of all of the light beams was conducted, and revealed that the primary source of phase shift in the interferometer were the forward-facing optical molasses beams, causing 105 mrad of phase shift. Overall, there were 206 mrad of phase shift observed due to scattered light in the system. No loss of coherence is observed due to this phase shift, but it represents a significant source of systematic error. This error is already mitigated by k-reversal, and can be further reduced by scattered light mitigation. Furthermore, the systematic error can be successfully removed through calibration if stable optical power can be achieved, which is straightforwardly achievable at the 0.1% level.

5. CONCLUSIONS

I have demonstrated a dynamic range improvement of >100x in an inertial measurement from a continuous atom interferometer. Fundamentally, this measurement is only limited by the current experimental apparatus, and could be used to measure the absolute phase of an inertial sensor in a near-static configuration. Compared to the prevailing literature, the work done here represents a 10x increase in bandwidth for a comparable dynamic range improvement, though likely a much higher dynamic range improvement is possible. The benefits of this measurement would also likely be improved by performing sub-interrogation time k-switching, allowing for the bandwidth of the measurement to be drastically improved. Continuing advances along this research path will be made possible by multiple co-located and co-propagating continuous interferometers, potentially leading to much greater dynamic range improvements at much better bandwidths.

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