Proceedings of the Seventh Meeting on CPT and Lorentz Symmetry (CPT'16), Indiana University, Bloomington, June 20-24, 2016

Improved Accuracy of Atom Interferometry Using Bragg Diffraction

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We study sub-part per billion systematic effects in a Bragg-diffraction atom interferometer relevant to a precision-measurement of the fine-structure constant. The multi-port nature of Bragg diffraction gives rise to parasitic interferometers, which we suppress using a "magic" Bragg pulse duration. The sensitivity of the apparatus is improved by the addition of AC Stark shift compensation, which permits direct experimental study of sub-ppb systematics. This upgrade allows for a $310\hbar k$ momentum transfer, giving an unprecedented 6.6Mrad measured in a Ramsey-Bordé interferometer.

1. Introduction

Atom interferometers have been used for tests of fundamental physics, such as the isotropy of gravity[1], the equivalence principle[2] (setting many new limits on parameters of the Standard Model Extension[3]), and the search for dark-sector particles[4]. The interferometer discussed here has been described in detail before.[5] Two cesium Ramsey-Bordé interferometers (RBIs) are operated in a simultaneous conjugate configuration, with each $2n$-photon beamsplitter formed by a Bragg pulse that splits the atoms by a total of $2n\hbar k$, where $\hbar k$ is the photon momentum, without changing the internal state of the atoms. A Bloch pulse is applied in the middle of the sequence, to provide additional momentum splitting by $2N\hbar k$. The interferometer has a total phase of (to leading order)

$$\Phi = 16n(n+N)\omega_r T, \tag{1}$$

where T is the separation time between the first and second laser pulses (also equal to that between the third and fourth), and $\omega_r = \hbar k^2/(2m)$ is the recoil frequency we seek to measure.

2. AC Stark shift compensation

As the pulse separation time is increased, random distortions in the wavefronts at short distance scales (arising, e.g., from speckle) of the Bragg and Bloch laser beams will result in spatially varying AC Stark shifts that lead to decoherence. To suppress this effect, we apply a beam from the same optical fiber as the Bragg and Bloch beams, with the same intensity but opposite single-photon detuning. This beam contains only a single frequency and thus does not drive Bragg transitions or Bloch oscillations. This beam compensates for the variable AC Stark shift.[6]

As a result, coherence can be observed with $N = 75$ up to a maximum pulse separation time of $T = 80\,\text{ms}$, as shown in Figure 1. The momentum splitting between the "fastest" and "slowest" arms of the interferometer is $2(n + 2N)\hbar k = 310\hbar k$, giving a $\Phi = 6.6\,\text{Mrad}$ - the largest measured phase in any RBI. Not only does this upgrade allow a measurement of α with a higher integration rate, it also permits the study of sub-ppb systematic effects.

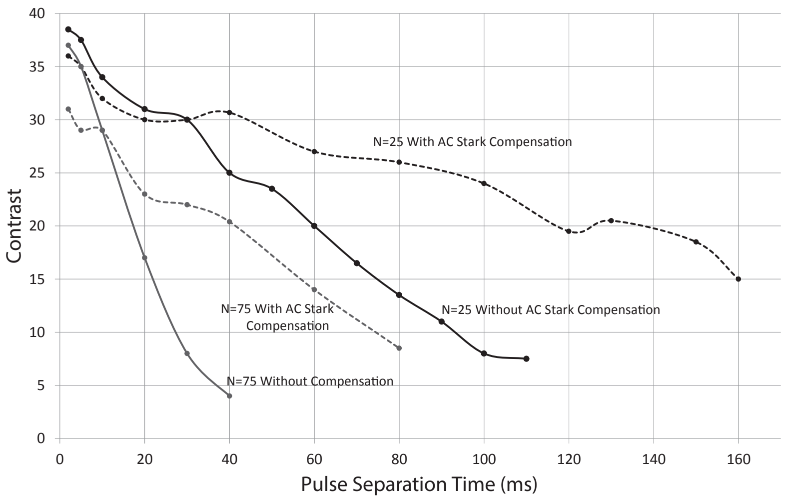

Fig. 1. Contrast versus pulse separation time for $N = 25$ and $N = 75$ Bloch oscillations, with and without AC Stark shift compensation.

3. Parasitic Interferometers

Because Bragg diffraction populates more than the two desired momentum states, it is possible to simultaneously create multiple RBIs. These interferometers will close at the same time as the main interferometer, and will not be suppressed by the Bloch pulse. The effect of a single parasitic interferometer of order n_1 on the outputs X,Y of a RBI of order n_0 is a sinusoidal variation of the measured recoil frequency. For an n_0=5 RBI, the dominant parasitic interferometer has a Bragg order of n_1=1. The population driven into an undesired order depends sensitively on the Bragg intensity and detuning from Bragg resonance. A "magic" duration, see Figure 2, minimizes this population and suppresses the parasitic interferometer, see Fig. 3.

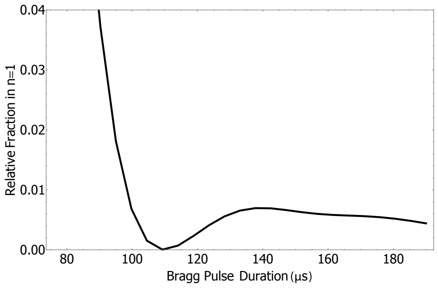

Fig. 2. Calculated fraction of atoms driven into $n = 1$ versus Bragg pulse duration (in units of 95 μs). This is a single-atom simulation, with the atom on Bragg resonance.

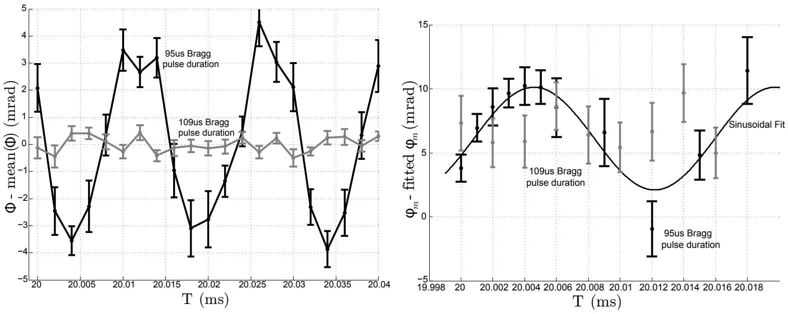

Fig. 3. Suppression of parasitic interferometers by choosing the "magic" pulse duration. Left: Simulation, Right: Experimental data

4. Conclusion

We expect that the technology will make further contributions to testing fundamental physics. Measuring the fine structure constant will contribute to the search for dark-sector particles; measurements of the gravitational Aharonov-Bohm effect[7] and of short-range gravity[8] appear feasible, and further tests of the equivalence principle will be performed, e.g. in space[9]. See also P. Asenbaum *et al.*, these proceedings.

Acknowledgments

We thank J. Cui for help in setting up the Stark-shift compensation and P.C. Kuan and S.Y. Lan for discussions. This material is based upon work supported by the National Science Foundation under CAREER Grant No. PHY-1056620, the David and Lucile Packard Foundation, and National Aeronautics and Space Administration Grants No. NNH13ZTT002N, No. NNH10ZDA001N-PIDDP, and No. NNH11ZTT001.

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