High resolution rotation sensor based on cold Rubidium atoms

Michael Gilowski, Christian Schubert, Thijs Wendrich, Peter Berg, Gunnar Tackmann,
Wolfgang Ertmer, and Ernst Maria Rasel
Institut of Quantum Optics, Leibniz University of Hanover,
Welfengarten 1, 30167 Hannover, Germany

***Abstract*— We report on our compact transportable cold atom inertial sensor for precision sensing of rotations. The sensor consists of a dual Mach-Zehnder type atom interferometer operating with laser-cooled ^{87}Rb. Raman processes are employed to coherently manipulate the matter waves. We present the latest inertial sensitive interferometer measurements and discuss the road map to reach the full potential of the sensor featuring a sensitivity of a few nrad/s/$\sqrt{\text{Hz}}$.**

I. Introduction

Atom interferometry has become an important technique for high sensitive measurements of various kinds and a series of experiments with impressive resolutions has been performed in fundamental physics and metrology. Measurements of the fine-structure constant α based on the photon recoil [1], of Earth's acceleration $\vec{g}$ [2] or the gravitational constant G [3] using gravimeters or gradiogravimeters are impressive demonstrations of the feasibility and potential of atom interferometry. Furthermore, high precision rotation measurements have been performed [4], [5] reaching a sensitivity comparable to state-of-the-art optical gyroscopes [6]. In this article we present the realization of such a high resolution rotational atom interferometer based on cold Rubidium 87 atoms [7]. The interferometric measurement of rotations is based on the Sagnac-effect [8], which indicates that a phase shift is induced between two interferometer paths which enclose an area $\vec{A}$, due to a rotation with the angular velocity $\vec{\Omega}$. This phase shift is then given by $\delta\varphi_{rot} = 4\pi E\vec{A}\vec{\Omega}/hc$, where E is the energy of the wave, h the Planck's constant and c the speed of light. Since this relation is also valid for light as well as for matter wave interferometers, the high potential of gyroscopes based on atoms is obvious. By comparing the phase shifts using the energies of matter and visible light, an improvement in the order of 10^{11} for atom interferometers is in principle possible. Besides high accuracy, the additional goals of the experiment are a good long-term stability for signal integration and a compact and transportable setup which is needed for measuring campaigns with other state-of-the-art gyroscopes, for example the ones described in Ref. [5], [6]. In this context, we are using laser cooled atoms in our interferometer allowing large enclosed areas of similar size as for thermal atomic beams and long interaction times while still retaining a compact experimental setup. Thus our sensor combines the advantages of the gyroscopes presented in Ref. [4] and [5]. The coherent beam splitters and mirrors for the atoms in our interferometer are realized by two photon Raman-processes, driving the hyperfine transition $5^2\text{S}_{1/2}$ $(F = 1, m_F = 0 \rightarrow F = 2, m_F = 0)$ of ^{87}Rb. During such a beam splitter process, also the momentum state of the two hyperfine ground states is changed leading to a spatial splitting or reflecting of the matter wave. Using a so-called $\pi/2-\pi-\pi/2$-sequence, it is possible to realize a Mach-Zehnder like interferometer geometry [9], which is besides rotations also sensitive for accelerations.

II. The Apparatus

In order to distinguish between phase shifts due to rotations and accelerations the sensor consists of two interferometers allowing a differential measurement [4]. The basic schematic of our experiment is sketched in Fig. 1. Two identical atomic sources [10] emit atoms on flat parabolic trajectories into the interferometer, but with opposite launch directions. Each source consists of a two-dimensional magneto-optical trap (2D-MOT) loading a subsequent 3D-MOT with a high flux of several 10^9 at/s. Using the moving molasses technique 10^8 atoms with a temperature of 8 μK are launched in each interferometry pulse. The forward drift velocity $\vec{v}_{at}$ can be tuned independently between 2.5-5 m/s with a relative uncertainty of $< 3\times10^{-4}$ to realize an optimal spatial overlap of both interferometers and a precise control of the enclosed area.

In a next step the atoms are state- and velocity-selectively transferred into the magnetically insensitive $|F = 1, m_F = 0\rangle$ ground state via a multi-stage preparation using precisely controllable laser manipulation. The velocity filtering is performed

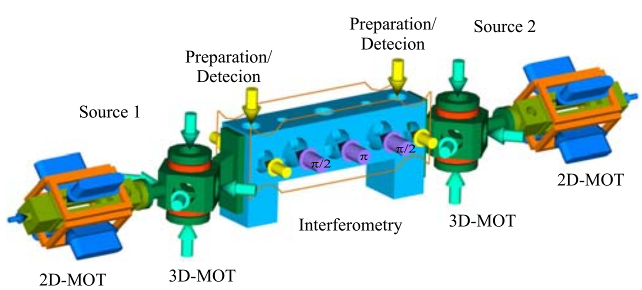

Fig. 1. Concept of the dual atom interferometer for high resolution inertial sensing. Two double MOT sources are attached on each side of the interferometry chamber. In this evacuated system we reach a pressure of 5×10^{-10} mbar.

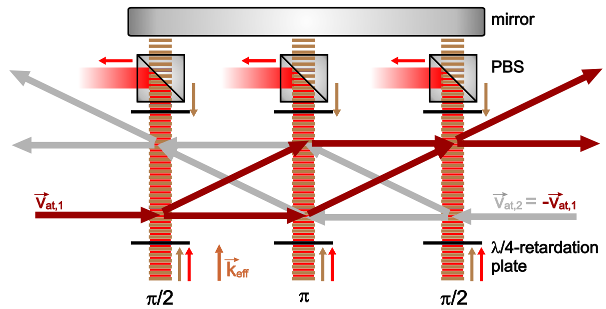

Fig. 2. New beam splitter configuration enables differential rotational measurement in the Mach-Zehnder like interferometer.

with a Raman-π-pulse, resulting in a velocity distribution in the direction of the Raman-beams which corresponds to a temperature of about 1 μK.

In the following interferometry region, the pair of Raman-light fields is implemented in a counter-propagating configuration leading to an effective momentum transfer of $\hbar\vec{k}_{eff}$ with $\vec{k}_{eff} = \vec{k}_1 - \vec{k}_2 \approx 2k_{1,2}$, where $\vec{k}_{1,2}$ is the wave vector of the two light fields, respectively. Using the experimental variables, the inertial phase shift can be written in the form:

$$\delta\varphi = \delta\varphi_{rot} + \delta\varphi_{acc} = 2\vec{\Omega}(\vec{k}_{eff} \times \vec{v}_{at})T^2 + \vec{k}_{eff}\vec{g}T^2 \quad (1)$$

For a given $\vec{k}_{eff}$ and T, which is the time between two interferometry pulses, as well as for $\pm\vec{v}_{at}$, what is realized in the dual interferometry scheme, the possibility to distinguish between phase shifts due to rotations and accelerations is clearly visible.

With a mirror the Raman-beams are reflected creating two possible beam splitting light pairs with $\pm\vec{k}_{eff}$. To get rid of one of the beam pairs we slightly tilt the mirror with respect to the atomic trajectory inducing a shift of the transition frequency of the two interferometer states due to the Doppler-effect [5]. In this method $\vec{k}_{eff}$ has a different sign for the two interferometers, respectively. Together with the interferometer dependant sign of $\vec{v}_{at}$ the sign of the rotational phase shift does not change in the two interferometers, while the sign of the phase shift due to accelerations is altering. In a second beam splitter setup, illustrated in Fig. 2, it is possible to realize a differential rotational measurement by making use of the polarization of the cross polarized beam splitter light fields. Using polarizing optics, one of the Raman-light fields can be reflected out after passing the interferometry chamber while the second one can be back-reflected by the mirror with zero-tilt. Thus, only one beam splitter pair remains and $\vec{k}_{eff}$ is the same for both interferometers. This setup is currently realized in our sensor. To minimize phase front fluctuations due to the imperfections of the flatness of the used beam splitter optics, high quality retardation plates, beam splitter plates (PBS) as well as the mirror are implemented.

Since the interferometers measure is a phase, phase noise of the Raman-lasers influences the interferometer signal and has to be suppressed. Using an optical phase-locked loop (PLL) the phase and frequency difference of the two lasers, which generate the beam splitting light fields, is sharply locked to a very stable microwave reference oscillator [11]. We obtain a Raman-laser phase noise impact on the interferometer phase noise of less than 1 mrad.

A phase shift imprinted during the interferometric cycle is in such a sensor geometry translated into a change of the distribution in the two ground states. Thus, we finally obtain the phase shift of each interferometer by using a state-selective fluorescence detection, applied after the interferometry sequence. We detect approximately several 10^7 atoms.

III. Results and Conclusion

A demonstration of a phase sensitive interferometry measurement with our sensor is shown in Fig. 3. Here, the beam splitter configuration with a tilted mirror was used. We obtain the interferometry fringes by sweeping the phase of the Raman-lasers with the PLL before the last interferometry pulse is applied. The time T between two Raman-pulses, all of them applied in a single interaction zone, is 0.5 ms and the π-pulse duration is about 10 μs. From this data we infer a signal-to-noise ratio of 46 and a contrast of 38%. The phase noise is about 20 mrad which is dominated by the electronical noise of the detection. With this setup we obtain a sensitivity of 4.7 mrad/s for a single shot.

After accomplishing the above mentioned beam splitter setup which provides an increased total interferometry time of $2T = 50$ ms by realizing three separate interaction zones, we can estimate from the presented "first shot" a sensitivity to rotations of 3×10^{-7} rad/s/$\sqrt{\text{Hz}}$. Further reduction of critical noise sources and improvements of the beam splitting process, where multi-photon transitions can drastically enlarge the enclosed interferometry area [12] are planed to increase the sensitivity to a level of a few nrad/s/$\sqrt{\text{Hz}}$.

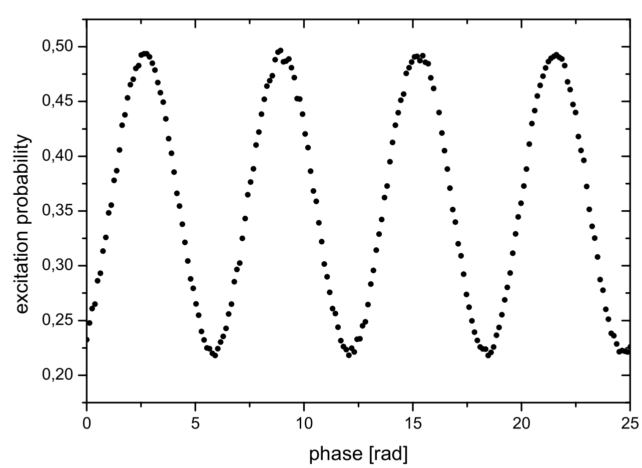

Fig. 3. Interference fringes of the described atom interferometer configuration. To observe the fringes, the phase difference between the two phase-locked Raman-lasers is scanned before the last interferometry pulse.

ACKNOWLEDGMENT

This work was supported in part by the Deutsche Forschungsgemeinschaft (SFB407, QUEST) and in part by the European Union (Finaqs). M.G. wants to thank the Max Planck Gesellschaft for financial support.

REFERENCES

[1] H. Müller, S.-w Chiow, Q. Long, Ch. Vo, S. Chu, Appl. Phys. B 84, 633-642 (2006).
[2] A. Peters, K.Y. Chung, S. Chu. Nature 400, 849 (1999).
[3] G. Lamporesi, A. Bertoldi, L. Cacciapuoti, M. Prevedelli, G.M. Tino, Phys, Rev. Lett. 100, 050801 (2008); J.B. Fixler, G.T. Foster, J.M. McGuirk, M.A. Kasevich, Science 315, 74 (2007).
[4] T. L. Gustavson, A. Landragin, M. A. Kasevich, Phys. Rev. Lett. 17, 2385 (2000).
[5] B. Canuel, F. Leduc, D. Holleville, A. Gauguet, J. Fils, A. Virdis, A. Clairon, N. Dimarcq, Ch.J. Bordé, A. Landragin, P. Bouyer, Phys. Rev. Lett. 97, 010402 (2006).
[6] K. U. Schreiber, T. Klügel, G. E. Stedman, J. Geophys. Res. 108, 2132 (2003).
[7] T. Müller, M. Gilowski, M. Zaiser, P. Berg, Ch. Schubert, T. Wendrich, W. Ertmer, and E.M. Rasel, Euro. J. Phys. D, DOI: 10.1140/epjd/e2009-00139-0.
[8] G. Sagnac, Compt. Rend. Des Sc. D. l'Acad. D. Sc. 157, 1410 (1913).
[9] Ch.J. Bordé, Phys. Lett. A 140, 10 (1989).
[10] T. Müller, T. Wendrich, M. Gilowski, C. Jentsch, E.M. Rasel, W. Ertmer, Phys. Rev. A 76, 063611 (2007).
[11] P. Cheinet, B. Canuel, F. Pereira dos Santos, A. Gauguet, F. Yver-Leduc, A. Landragin, IEEE Trans. Instrum. Meas. 57, 1141 (2008).
[12] T. Lévèque, A. Gauguet, F. Michaud, F. Pereira Dos Santos, A. Landragin, arXiv:0904.3266 (2009).