Atom interferometer using a free oscillation of Bose-Einstein Condensate on an atom chip

Ken'ichi Nakagawa1,2, Munekazu Horikoshi1*

1Institute for Laser Science, University of Electro-Communications, 1-5-1 Chofugaoka, Chofu, Tokyo, 182-8585 Japan

2CREST, Japan Science and Technology Agency, 4-1-8 Honcho, Kawaguchi, Saitama 332-0012, Japan

nakagawa@ils.uec.ac.jp

Abstract. We have demonstrated a novel atom interferometer which uses a free oscillation of 87Rb BEC atoms in a magnetic harmonic potential on an atom chip. This interferometer can effectively suppress the dephasing due to the trap potential by applying two Bragg laser pulses with an time interval T equal to the oscillation period of the axial mode of the magnetic trap. We observed a high contrast (~30 %) interference fringe signal for T = 58 ms. When we increased the time interval T to 97 ms, an interference fringe was washed out by the random phase fluctuation. We attributed this phase fluctuation to the external vibrational noise from the floor.

1. Introduction

Recently many attentions have been paid to atom interferometers using Bose-Einstein condensates (BEC) in a trap or waveguide [1]. Atom interferometers using trapped atoms instead of free falling atoms can offer the future prospect of realizing longer interrogation time and thus higher sensitivity than those of the conventional atom interferometers with free falling atoms. However, the dephasing effects of condensate atoms in a trap due to the atom-atom interaction and the trap potential has limited the maximum coherence time to about 10 ms [1-2].

In this paper, we present a novel atomic interferometer using a free oscillation of atoms in a magnetic harmonic potential on a chip [3]. With this new interferometer, we can suppress the dephasing due to the trap potential and we can realize a long coherence time of more than 50 ms.

2. Experimental setup

We use an atom chip for the production and manipulation of condensate atoms [4]. The atom chip used in the experiment is shown in Fig. 1. Using standard photolithographic and electroplating techniques, a gold wire pattern for the micro magnetic potential is fabricated on a Si substrate. A magnetic wave guide potential is produced by the combination of the magnetic field of the current (Iz) through the Z-shaped wire (Z-wire) and the uniform bias field (B0) (Fig. 1 (b)). A current through the crossed wire is additionally used to realize a harmonic potential at the center of the Z-wire.

Using this atom chip, we can produce a Bose-Einstein condensate (BEC) of about $10^4$ 87Rb atoms in the F=2, m_F=2 state with an evaporation time of about 5s. Condensate atoms are trapped around
Fig. 1. Atom chip and magnetic potential. (a) Atom chip. (b) A wire configuration for the magnetic trap potential. (c) Trapped atoms in the magnetic potential above the chip.

100 µm above the wire surface (Fig. 1 (c)). In the following interferometer experiment, in order to split the condensate atoms into two components, counter-propagating two laser beams are incident on the condensate atoms (Fig. 2 (b)) along the axial direction of the trap.

3. Trapped BEC interferometer

A first BEC interferometer on an atom chip was demonstrated by Wang et al.[1]. They realized an atom Michelson interferometer using an optical standing wave light field as an atom beam splitter, and they observed the interference fringe signal for the interaction time up to 10 ms [1]. Following this first experiment, we realized a Mach-Zehnder atom interferometer using an optical Bragg diffraction as an atom beam splitter. We observed the high-contrast interference fringe signal for the interaction time up to 1 ms. However, the fringe contrast became degraded when we increased the interaction time and the trap frequency [2]. We attributed it to the dephasing effect due to the trap potential and the atom-atom interaction.

The dephasing effect due to the trap potential is caused by the velocity change of the condensate when the condensate move in the potential. In order to eliminate this dephasing effect, we have proposed a novel interferometer using a free oscillating BEC in a harmonic potential (Fig. 2). We apply two optical Bragg pulses to the BEC in a harmonic trap with a time interval T between two pulses. A first $\pi/2$ Bragg pulse splits a BEC in a trap into two components, one in $p = 0$, and the other in $p = 2\hbar k$ momentum state, respectively. Two BEC components freely evolve in a harmonic potential, and then the second $\pi/2$ pulse is applied to recombine two components after a time interval T from the first pulse. If T is exactly equal to the trap oscillating period $T_0 = 2\pi/\omega_0$, where $\omega_0$ is the axial trap frequency, the velocity of the separated condensate is returned to the initial value at the first pulse, and the dephasing due to the trap potential is eliminated.

Fig. 2. Schematic drawing for the atom interferometer using a free oscillation of BEC.
Figure 3 shows the experimental results. We plot the fraction of atoms in the momentum state \( p = 0 \) given by \( P_{2h} = N_{2h}/(N_0 + N_{2h}) \), where \( N_0 \) and \( N_{2h} \) are the number of atoms in the momentum state \( p = 0, \), respectively. At first, we set the trap frequency \( \omega_0/2\pi \) to 19 Hz. Thus the time interval \( T \) is set equal to the corresponding trap oscillation period \( T_0 = 2\pi/\omega_0 \) of about 59 ms. The observed signal shows a clear interference fringe with a fringe contrast of about 30% (Fig. 3 (a)). This result proves that the dephasing effect due to the trap potential is effectively reduced.

Next, we set the trap frequency \( \omega_0/2\pi \) to 10 Hz, thus \( T = 97 \) ms. The observed signal is randomly distributed between 0.2 and 0.7, and the interference fringe is hardly seen in the signal (Fig. 3 (b)). We attribute this run-to-run fluctuation of the signal in Fig. 3 (b) to the internal and/or the external phase noise not to the dephasing effect. To confirm this assumption, we detune the time interval \( T \) from the trap oscillation period \( T_0 \). The amplitude of the signal fluctuation is maximum at \( T = T_0 \), while it decreases for \( T \neq T_0 \) (Fig. 3 (c)). If \( T \neq T_0 \), the velocity of the condensate is not exactly returned to the initial one, and thus the dephasing is not completely eliminated.

One of the possible phase noise source is the atom-atom interaction [5,6]. When a BEC with \( N \) atoms is coherently split into two components, a relative atom number \( \Delta N (= N_1 - N_2) \) is different from shot-to-shot, where \( N_1 \) and \( N_2 \) are the number of atoms in each component. This shot-to-shot variation of \( \Delta N \) induces the relative phase difference \( \Delta \phi \) between two components due to the atom-atom interaction [5]. This phase fluctuation increases linearly with time, and it limits the maximum coherence time of the trapped condensates. The coherence time can be extended by using a number squeezed state of condensates [6]. For our experimental condition, the maximum coherence time is estimated to be 400 ms, which is still longer than 97 ms.

Another noise source is the external vibration from the floor. We analyzed the phase change of the interferometer signal due to the vibration of the experimental apparatus, and we found that this interferometer acts as a resonant-type accelerometer with a maximum phase sensitivity at the trap frequency of 10 Hz for \( T = 97 \) ms [3]. Our experimental apparatus including the atom chip and the laser optics is put on the air-dumped optical table. The interferometer signal is largely affected by the large vibrational noise around the natural frequency of the optical table, which is about 2 Hz. We evaluated the phase fluctuation of the interferometer signal from the measured vibrational noise of the optical table, and it is nearly consistent with the experimental results. Thus we attributed the observed large shot-to-shot random phase fluctuation for \( T = 97 \) ms (Fig. 3 (b)) to the external vibration noise rather than the phase noise due to the atom-atom interaction.

The present experiment proved that the atom interferometer using a free oscillation of atoms in a harmonic trap is promising in terms of long interaction time of much longer than 100 ms which cannot be easily realized in the conventional atom interferometer using free falling atoms. Recently Burke et al. demonstrated an extension of the interaction time up to 0.91 s using the same method as ours, but
they also observed the shot-to-shot random phase fluctuation due to the vibrational noise [7]. Thus if we employ an active stabilization of the optical table to effectively reduce the vibrational noise in the frequency region from 1 to 10 Hz, we will be able to realize a highly sensitive atom interferometer for the precision measurement of such as Newtonian gravitational constant [8].

4. Conclusion
We have demonstrated a novel interferometer based on a free oscillation of condensate atoms in a magnetic harmonic potential on an atom chip. It has been seen that the dephasing due to the trap potential could be effectively cancelled by setting the time interval between two Bragg pulses equal to the trap oscillating period, and an interference signal with a high fringe contrast of 30% was observed for the time interval of 58 ms. For a longer time interval of 97 ms, the dephasing effect was still eliminated, however, the interference fringe was washed out by the low frequency external vibrational noise.

Acknowledgments
This work was partly supported by a Grant in Aid for Science Research (No. 17340120) from the Ministry of Education, Science, Sports, and Culture, “Ground-Based Research Program for Space Utilization” promoted by Japan Space Forum.

* Present address: ERATO Macroscopic Quantum Control Project, JST, 2-11-16 Yayoi, Bunkyo-Ku, Tokyo 113-8656, Japan

References
[1] Wang Y, Anderson D Z, Bright V M, Cornell E A, Diot Q, Kishimoto T, Prentiss M, Saravanan R A, Segal S R and Wu S 2005 Atom Michelson Interferometer on a Chip Using a Bose-Einstein Condensate Phys. Rev. Lett. 94 090405
[2] Horikoshi M and Nakagawa K 2006 Dephasing due to atom-atom interaction in a waveguide interferometer using a Bose-Einstein condensate Phys. Rev. A 74 031602(R)
[3] Horikoshi M and Nakagawa K 2007 Suppression of dephasing due to a trapping potential and atom-atom interactions in a trapped-condensate interferometer Phys. Rev. Lett. 99 180401
[4] Horikoshi M and Nakagawa K 2006 Atom Chip based fast production of Bose-Einstein condensate Appl. Phys. B 82 363
[5] Castin Y and Dalibard J 1997 Relative phase of two Bose-Einstein condensates Phys. Rev. A 55 4330
[6] Jo G -B, Shin Y, Will S, Pasquini T A, Saba M, Ketterle W, Pritchard D E, Vengalattore M and Prentiss M 2007 Long Phase Coherence Time and Number Squeezing of Two Bose-Einstein Condensates on an Atom Chip Phys. Rev. Lett. 98 030407
[7] Burke J H T, Deissler B, Hughes K J, Sackett C A 2008 Confinement effects in a guided-wave atom interferometer with millimeter-scale arm separation Phys. Rev. A 78 023619
[8] Lamporesi G, Bertoldi A, Cacciapuori L, Prevedelli M, Tino G M 2008 Determination of the Newtonian Gravitational Constant Using Atom Interferometry Phys. Rev. Lett. 100 050801