Letter

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Probing Bloch oscillations using a slow-light sensor

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Abstract: We implement slow-light under electromagnetically induced transparency condition to measure the motion of cold atoms in an optical lattice undergoing Bloch oscillation. The motion of atoms is mapped out through the phase shift of light without perturbing the external and internal state of the atoms. Our results can be used to construct a continuous motional sensor of cold atoms.

Keywords: Bloch oscillation; quantum sensor; slow light.

Motional sensors built upon cold atoms quantum technologies have led to many exciting applications in geodesy and studies of fundamental sciences [1]. It has been used to measure inertial effects, such as gravity [2, 3], gravity gradient [4], and absolute rotation [5]. Precise measurements of the motion of quantum particles have been used, for example, to test the weak equivalence principle [6], determine the fine structure constant [7], and measure the Newton's constant of gravitation [8]. The conventional way of detecting the motion of atoms leans on the Doppler sensitive two-photon process, where the Doppler shift of light relative to the atoms is measured by counting the population of the atoms in a specific quantum state through fluorescence detection [9, 10]. As a result, the state of the atoms is destroyed, and reloading the atoms is required for each data point.

The slow-light effect has been proposed and demonstrated to detect the motion of atoms using the dispersion of an ensemble of atoms [11–13]. When light passing through an ensemble of atoms, the motion of the atoms is mapped into the phase shift of the light which is proportional to the time light spent in the medium as

$$\Delta\phi = k_{eff} v\tau, \qquad (1)$$

where k_{eff} is the effective wavenumber of the light, v is the center-of-mass velocity of the atomic ensemble, and τ is the time light spent in the medium. Therefore, the sensitivity of the phase shift measurement scales with the time τ. This is also termed as the light-dragging effect in the pre special relativity era. The sensitivity can be enhanced by using slow-light effect, which allows the increase of the traveling time inside the atoms by several orders of magnitude. One of the popular ways for slow light is to add an auxiliary light to modify the dispersive property of the medium, the so-called electromagnetically induced transparency (EIT) condition [14]. Here, we use the slow-light sensor under EIT condition to measure the velocity of an ensemble of atoms under Bloch oscillations (BOs).

BO occurs when quantum particles in a periodic potential subject to a weak additional constant force. It has been observed in various physical systems. For cold atoms in a periodic optical potential, the constant force F can be created by ramping the relative frequency of the lattice beams in time [15]. The corresponding acceleration can be determined by $a = \mathrm{d}(\Delta\omega/2k)/\mathrm{d}t$, where $\Delta\omega$ is the relative angular frequency of the lattice beams and k is the wavenumber of the lattice beams.

We first Doppler cool an ensemble of ^{85}Rb atoms from the background vapor in a magneto-optical trap followed by the sub-Doppler cooling to achieve a temperature of 10 μK. For the necessity of efficiently loading the atoms into the optical lattice, we implement two-dimensional degenerate Raman sideband cooling (RSC) to cool the atoms down to nearly recoil temperature in a few milliseconds [16]. The one-dimensional optical lattice beams are generated from the RSC beams, 12 GHz red-detuned from the ^{85}Rb D2 transition. The frequencies and intensities of the counter-propagating lattice beams are controlled by a pair of acoustic-optical modulators separately. The lattice beams waists are approximately 3 mm, and the potential depth is about 7ER, where ER is the recoil energy.

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To create the BOs, the relative frequency of the two lattice beams is ramped linearly at a rate of 75 MHz/s when the lattice power is full, which corresponds to an acceleration of 30 m/s^2. The duration of the lattice also includes the rising and falling time of 0.8 and 0.1 ms, respectively. The Bloch period $\tau_B = h/(Fd)$ at this ramping rate is calculated as 400 µs, where h is the Planck constant and d is the lattice spacing. Due to the finite temperature of the atoms, our BO efficiency is about 55%.

We use the hyperfine ground states $F = 2$ and $F = 3$ of ^{85}Rb and the excited state $F' = 3$ of the D1 line to form the three-level Λ-type EIT system. The control beam that is used to create the slow-light medium for the probe beam is resonant on the $F = 3$ to $F' = 3$ state while the probe beam is resonant on the $F = 2$ to $F' = 3$ state. The optical alignment of the experiment is shown in Figure 1. The control and the probe beams are aligned relatively at 185º and nearly along the lattice axis. The effective wavenumber at this angle is $k_{eff} = 1.6 \times 10^7$ m^{-1}. Both beams are linearly polarized and perpendicular to each other. The probe beam is focused at the atoms' position with a waist of 1 mm, and the control beam size is made a few times larger than the atomic ensemble size.

To measure the phase shift of the probe beam, we modulate it at 70 MHz and split half of the power as a reference beam. Both beams are detected separately by two fast photodiodes, and the phase shifts of the 70 MHz beatnotes are compared on an oscilloscope to determine the velocity of the atomic ensemble. One cycle of phase shift corresponds to 1/70 MHz = 14.29 ns. During the measurement, the control beam is switched on 0.5 ms before the probe beam to pump the atoms into the $F = 2$ state. The pulse shapes of the control and the probe fields are 1 ms square pulse and 5 µs full width at half maximum of Gaussian pulse, respectively.

Figure 2 shows the relative delay time between the positive and negative directions of BOs as a function of the ramping time of the lattice beams' frequency. The positive direction is defined along the probe beam direction. The opposite direction of BOs is implemented by swapping the relative frequency detuning. We measure the delay times in each direction by comparing the phase shifts between the probe and the reference beams and subtract the

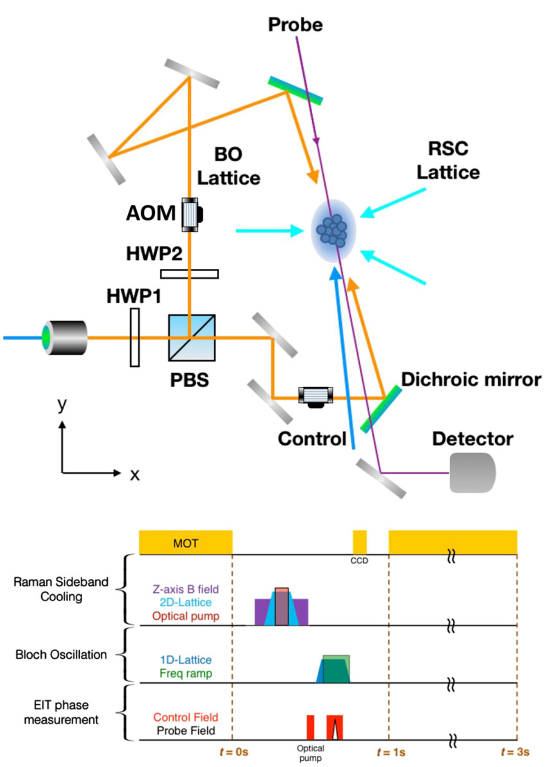

Figure 1: Top: The optical setup for Bloch oscillation measurements using slow light. The frequencies and optical power switching of the counter-propagating optical lattice beams are controlled by two independent acousto-optical modulators (AOMs). During the Bloch oscillations, the frequency of one of the AOMs is fixed and that of the other one is ramped. The arrow in blue is the control beam, and the arrow in purple is the probe beam. PBS: polarizing beam splitter. HWP: half-wave plate. The HWP 1 is used for balancing the intensities of the lattice beams and the HWP 2 is used to match the polarizations of both beams. The reference beam for the probe beam is not shown. Bottom: Timing sequence of the experiment. Each cycle consists of 2 s of loading cold atoms and 1 s of the measurement. The charge-coupled device is used to image the size and position of the atomic ensemble in the x–y plane. The first control beam pulse is used to pump atoms after RSC to $F = 2$ state.

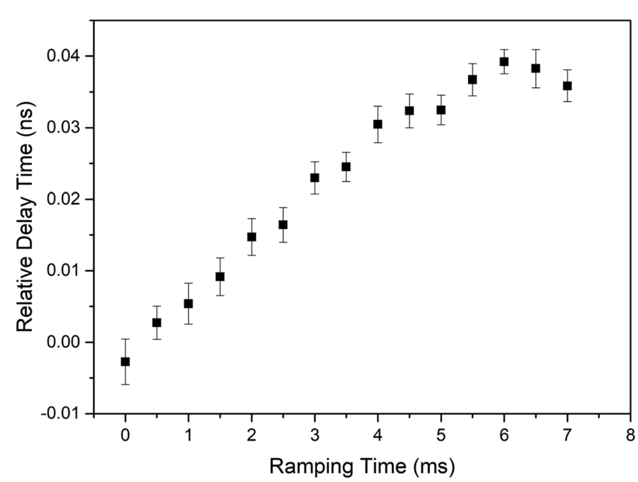

Figure 2: Relative delay time between the positive and negative directions of Bloch oscillations (BOs) as a function of the ramping time, where the positive direction of BOs is defined in the probe beam direction. Each data point is a subtraction of the delay times of both directions. The error bars represent the standard errors of 75 s of measurements.

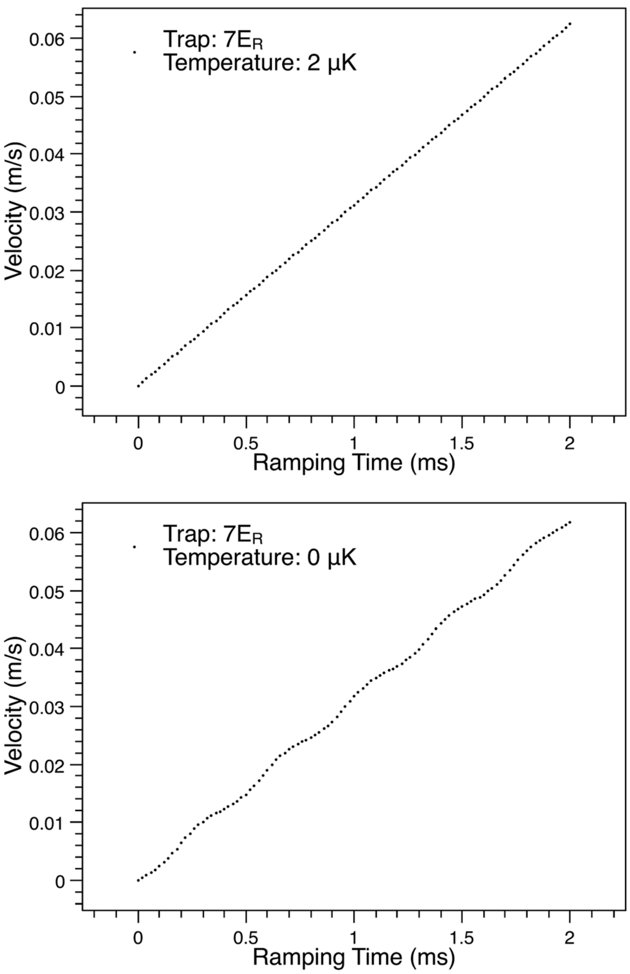

Figure 3: Calculation of the velocity as a function of the ramping time with 30 m/s^2 of acceleration and 7 E_R optical potential. Top: 2 μK atoms' temperature. Bottom: 0 μK atoms' temperature.

measurements of positive direction from the negative direction measurements to remove any systematic shifts that are not related to the direction. The time separation between each data point is set at 500 μs. Each data point is an average of 75 s data acquisition, and the precision at this data rate is 5 ps. The main noise is due to the fluctuation of atoms' density from shot to shot that changes the group delay of the probe light.

We study the velocity of atoms under BOs with our parameters theoretically. Figure 3 shows the calculation of 2 and 0 μK atoms' temperature in $7E_R$ trapping potential. Our experimental results show a similar trend as the calculation despite with low resolution on the velocity. The low resolution is due to the low optical density of atoms in the shallow lattice potential. As the temperature of the atoms in the third dimension is not cooled by the 2D RSC, the majority of the atoms are lost when we load them into the optical lattice. The phase shift ceases to increase after 6 ms due to the single-photon scattering of the lattice beams.

To observe stepwise BOs, the temperature, as well as the lattice potential, need to be further decreased. Cooling in three dimensions can increase the loading efficiency to achieve a larger optical depth, which would help to improve the resolution of the phase measurements with a longer delay time. Continuous monitoring of the phase is possible by accumulating a large set of data with a longer probe beam pulse. Since the control beam creates the quantum interference on the excited state for the probe beam so that absorption is minimized, destruction on the external and internal atomic states is greatly suppressed. Our method could potentially be designed as a quantum inertial sensor that is complementary to other types of sensors.

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