Large Momentum Beamsplitter using Bloch Oscillations

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The sensitivity of an inertial sensor based on an atomic interferometer is proportional to the velocity separation of atoms in the two arms of the interferometer. In this paper we describe how Bloch oscillations can be used to increase this separation and to create a large momentum transfer (LMT) beamsplitter. We experimentally demonstrate a separation of 10 recoil velocities. Light shifts during the acceleration introduce phase fluctuations which can reduce the fringes contrast. We precisely calculate this effect and demonstrate that it can be significantly reduced by using a suitable combination of LMT pulses. We finally show that this method seems to be very promising to realize a LMT beamsplitter with several tens of recoils and a very good efficiency.

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Over the past two decades, the impressive advances on the control and the manipulation of atomic de Broglie waves by coherent light pulses had led to the emergence of highly sensitive atomic interferometers[1–5]. Atom interferometry is based on coherent splitting and recombination of atomic wavepackets. The sensitivity of the atomic interferometer, which is proportional to the spatial separation of the wavepackets, can be enhanced by increasing the interaction time. In some experiments, this time is limited by the size of the vacuum cell: for example in gravity measurement, because of the free fall this time is limited by the size of the vacuum cell: for this time is limited by the size of the vacuum cell: for example in gravity measurement, because of the free fall this time is limited by the size of the vacuum cell: for example in gravity measurement, because of the free fall this time is limited by the size of the vacuum cell: for example in gravity measurement, because of the free fall.

The velocity splitting is usually achieved by using coherent momentum exchange between atoms and light (Raman or Bragg transition)[7]: with such a process the atoms are prepared in a superposition of two states with a well control relative velocity. In the case of Raman transitions and first order Bragg transitions (the most widely used configurations), this velocity difference \( \delta v \) is \( 2v_r \), where \( v_r \) is the recoil velocity. To circumvent the limitation due to the time measurement, one can enhance the interferometer sensitivity by increasing the velocity separation between its two arms. Several attempts have been investigated in this direction[8–13].

In this paper, we investigate a method to realize the momentum transfer using the so called "Bloch oscillations" (BO) [14, 15]. In this scheme, the large momentum transfer beamsplitter (LMTBS) is obtained in a two step process: the first one is a regular beamsplitter which creates two coherent wavepackets by transferring 2 recoil velocities while the second one is a large momentum transfer pulse (LMT pulse), that uses BO to coherently accelerate the atoms of one of the two wavepackets. When the beamsplitter is used to recombine the wavepackets, the order of the two steps is reversed. This method was initially suggested in Ref. [11], where a proof of principle experiment is described.

Compared to other methods, BO allow to transfer a large number of recoils with a high efficiency. This method seems therefore to be the most suitable for high precision measurements. In this letter we focus on one of the main systematic effects which is due to level shift of atoms in the lattice and produces a large phase shift in the interferometer. This phase shift depends on the position of the atoms in the laser beam and the motion of the atoms induces phase fluctuations which reduce the fringes contrast. It is especially large in our experiment in which, compared to Ref. [11], we use a non degenerate gas. We calculate this effect and demonstrate that it can be significantly reduced by using a suitable combination of LMT pulses.

The principle of Bloch oscillations [15] consists in shining on the atoms two counterpropagating laser beams of similar frequencies (\( \nu \) and \( \nu + \delta \nu \)). The interference of the two lasers results in a moving optical lattice of depth \( U_0 \) whose velocity is proportional to \( \delta \nu \). When this lattice is accelerated, and under specific conditions, the atoms are coherently accelerated. Because of the periodic potential, the eigenenergies of the system exhibit a band structure [16], each eigen state being described by a quasimomentum \( \mathbf{q} \) defined modulo \( 2\hbar k \) (where \( k = 2\pi / \lambda \) is the laser wave vector) and a band index \( n \). The figure 1 represents this band structure, where we have unfold the first Brillouin zone. There is a gap between bands either at the center (\( q = 0 \)) or at the edge of the first Brillouin zone (\( q = \pm \hbar k \)) when atoms are resonantly coupled. When an atom in the first band is subjected to a constant and uniform force, its quasimomentum increases linearly with time. If the force is weak enough to avoid non-adiabatic transitions, the atom stays in the first band and therefore has a periodic motion (Bloch oscillations [17]). Oscillations can also occur in higher bands. However, the bandgap decreases with higher band index. Therefore, if an atom passes through the crossing at a given speed,
the probability to make an adiabatic transition (to stay in the same band) will be higher for low value of the band index.

The principle of the large momentum transfer beam-splitter consists in creating a superposition of two wavepackets separated by 2 recoil velocities using, in our experiment, a Raman transition. The atoms are then loaded in the optical lattice so that one wavepacket is in the first band (A, see Fig. 1) and the second in the third band (B). This is the case when the velocity of the lattice is chosen such that the relative velocity of the first wavepacket lies between 0 and \( v_r \) and of the second between \( 2v_r \) and \( 3v_r \). A constant acceleration (which acts like a force in the frame of the lattice) is then applied. It is chosen small enough so that the atoms in the first band have a large probability to make an adiabatic transition but high enough so that the atoms in the third band change band. Each oscillation increases the momentum of the atoms by \( 2\hbar k \). On the other hand, the atoms in the third band (atoms that change band) are not accelerated.

The figure 2 depicts the probability for an atom to stay in its band as a function of the lattice amplitude for the first and third band (solid/blue and dashed/red line respectively). There is clearly an intermediate regime where the probability \( \eta_{11} \) for an atom to stay in the first band is high whereas the probability \( \eta_{33} \) for an atom to leave the third band (and reach the fourth one) is also high. For an acceleration of 4 recoils in 200 \( \mu s \), the total probability \( \langle \eta = \eta_{11} \eta_{34} \rangle \) (diamond) presents a maximum around \( U_0 = 8E_r \). The value of the maximum (97\%) depends on the duration of the acceleration and increases with this parameter.

We have plotted on the right side of Fig. 2 the total efficiency \( \eta \) as a function of the initial momentum \( p_0 \). This efficiency is computed including the loading and unloading of the atoms in the lattice: it is initially ramped up during a time \( t_{\text{adiab}} \), then accelerated during \( T_{\text{acc}} \) and ramped down during \( t_{\text{adiab}} \). By switching adiabatically up and down the lattice amplitude, the atoms from plane wave states are transferred to Bloch states and \textit{vice versa}. As this process is not fully adiabatic, the efficiency of the LMT is reduced. At the center and the edge of the first Brillouin zone (\( q_0 = 0 \) and \( q_0 = 1 \)), the efficiency is strongly reduced because the atoms cannot be loaded adiabatically in the lattice (those points are initially degenerate). For the chosen parameters (\( t_{\text{adiab}} = 150 \mu s \), \( T_{\text{acc}} = 200 \mu s \), \( N = 2 \) oscillations, \( U_0 = 8E_r \)), we see that the efficiency is larger than 95\% on a large zone. An important issue is to maximize the width in initial momentum where the process is very efficient. Indeed the atoms used in the interferometer have an initial velocity distribution selected by the Raman beam. The wider is the initial velocity distribution loaded into the LMT pulse, the higher is the number of atoms that contributes to the interferometer and so is the signal to noise ratio. We have optimized the efficiency by varying the amplitude and the temporal parameters keeping the total time \( 2t_{\text{adiab}} + T_{\text{acc}} = 500 \mu s \) constant.

One of the main drawbacks of the LMTBS based on Bloch oscillations is the light shift of the atoms in the lattice. In the case of a blue detuned lattice, the atoms in the first band are in a dark region and are almost not shifted, whereas the non-accelerated atoms in excited bands see an average shift corresponding to the mean value of the potential of the lattice. For typical parameters, this light shift, much larger than \( 2\pi \), must be canceled in order to run the interferometer. This cancellation occurs in the Mach-Zehnder configuration described on Fig. 3-A. The configuration used for the Raman pulses is similar to a regular interferometer with four \( \pi/2 \)-pulses and the LMT pulses are added inside each pair of \( \pi/2 \) pulses used either for selection or measurement (see the temporal sequence of Fig. 3-A). With this scheme, the LMT pulses are applied symmetrically on each arm of the interferometer, i.e., one arm of the interferometer is initially in the first band and then in an excited band and
vice versa for the other arm. Therefore, the phase shift accumulated on each arm is the same and there is no systematic effect if the laser intensity seen by the atoms is constant. However, this is not the case because of temporal fluctuations of the laser intensity (leading to a phase noise in the interference pattern) or motion of the atoms through the spatial profile of the laser beam (leading to a reduction of the fringes contrast). This last effect is not negligible in our experiment: indeed with our experimental parameters, the typical relative variation of the laser intensity is about 50 mR, leading to a phase shift of \( \Delta \phi = 3 \text{ rad} \). Consequently, there is a complete suppression of fringes.

In order to run the interferometer, we use a sequence (see Fig. 3-B) with 8 LMT pulses instead of 4. After (or before) each \( \pi/2 \) pulses, we accelerate successively each arm of the interferometer with two LMT pulses of opposite directions. With this scheme, the second LMT pulse compensates about 90% of the light shift [20]. The sensitivity of the interferometer to a variation of the intensity is then reduced by a factor of 10 compared to the 4 LMT pulses interferometer. Typically, the phase shift is \( \Delta \phi = 0.3 \text{ rad} \) and does not affect significantly the contrast of fringes. In the experiment, there is a correlation between the velocity and the position of the atoms due to the time of flight before the beginning of the interferometer. This results in a biased variation of the intensity which leads to a systematic effect in the interferometer. This effect can be canceled by inverting the order of the two LMT pulses for each beamsplitter.

The experimental setup is similar to the one described in [18]. We use \(^{87}\text{Rb}\) atoms cooled using a magneto-optical trap followed by an optical molasses. The Raman beams, in a vertical configuration, are produced by two phase locked laser diodes and an acousto-optic modulator (AOM) used to control the shape of the \( \pi/2 \) pulses. The Raman beams are brought to the science chamber using an optical fiber. In order to reduce the phase noise, a single polarization maintaining fiber is used. One of the two beams, selected by its polarization, is retroreflected in order to realize a counterpropagating transition.

The Bloch beams are produced by a Ti:Sa laser. A new scheme has been implemented in order to reduce the phase noise of the Bloch beams, which affects the interferometer. As for the Raman beams, a single fiber and a retroreflecting mirror are used to create the optical lattice. But in contrary to the Raman beams, both beams used for BO are retroreflected. By sending to the AOM two frequencies (\( \nu \) and \( \nu + \delta \nu \)) we create four lattices, one at the velocity of the atoms and three other lattices (one with the opposite velocity and two at rest). In the experiment, we wait about 10 ms between the end of the molasses and the beginning of the interferometer. Because of the gravity, the velocity of the atoms is then about 20 recoils and the three other lattices are sufficiently out of resonance to not disturb the interferometer. The amplitude and frequencies sent to the AOM are controlled using an RF chain based on an arbitrary waveform generator (similar to the one described in [18]). In order to measure the velocity change of atoms between the first part and second part of the interferometer, the frequencies of both the Raman and Bloch beams are changed in an identical way. The frequency of the central peak corresponds then to the Doppler effect induced by the variation of velocity.

The left side of Fig. 4 shows the proportion of atoms detected in the internal state \( F = 1 \) as a function of the frequency difference between the selection and the measurement. The fringes separation is \( \delta \nu_{\text{sep}} = 50 \text{ Hz} \) for this sequence. It corresponds to an effective time \( T_{\text{eff}} = 1/\delta \nu_{\text{sep}} \) of about 20 ms. We can compare this periodicity with the periodicity of fringes of an interferometer without LMT Bloch pulses. With the delay \( T_{\text{Ramsey}} \) of 5 ms between the beginning of the two Ramsey pulses, the periodicity would be 200 Hz. There is a gain of about 4 due to the use of LMT pulses.

On the right side of Fig. 4 we have plotted \( T_{\text{eff}} \) for three different durations of the selection: keeping the same \( \pi/2\)-Bloch-Bloch sequence, we change \( T_{\text{Ramsey}} \). In the inset of the figure, we have plotted the gain in resolution (ratio between the effective time and \( T_{\text{Ramsey}} \)) as a function of \( T_{\text{Ramsey}} \). At the limit where \( T_{\text{Ramsey}} \) is long, the duration of the LMT Bloch pulses can be neglected and the gain is exactly \( 2N + 1 \), i.e., 5 for our parameters. At shorter times, this gain is smaller. The predicted effective time is plotted on Fig. 4 (solid line). The good adjustment between the predicted time and our experimental data is a strong indication that the oscillations

![FIG. 3: Temporal sequence of the two interferometers with 4 and 8 LMT pulses. Bottom: intensity of the Raman (dashed line) and Bloch (solid line) beam; Top: trajectories of the atoms in the two arms; dashed and solid lines correspond to the two internal states of the atom.](image-url)
observed are due to the LMT pulses.

The amplitude of the signal is roughly 10 times smaller than the amplitude without LMT pulses. Different sources seem to contribute to these losses of amplitude. Our model does not take into account the non resonant lattices due to the retroreflecting configuration. Also, as explained earlier in the paper (Fig. 2), we have to take into account the initial distribution in momentum. We calculate that in the optimal configuration the total efficiency for 8 pulses is about 50%. This is the maximal efficiency and higher losses are actually expected because the intensity of the lattice is not well controlled and also is not constant over the atomic cloud. Spontaneous emission, estimated for our parameters to 4% for each of the LMT pulses, leads also to an additional reduction of 30% of the signal. Using a laser beam with a wider waist, a higher intensity (and a larger detuning) should allow us to reduce significantly those effects.

In order to further increase the velocity separation, one can imagine to have a two step process: the first step is identical to the one described earlier, with two Bloch oscillations. For the second step, we can increase adiabatically the depth of the lattice and then use a larger acceleration. A long time (and a relatively weaker lattice) is needed in order to realize the first separation with adiabaticity. The parameters of the LMT pulses are: $t_{\text{adiab}} = 150 \, \mu s$, $T_{\text{acc}} = 200 \, \mu s$, $N = 2$ oscillations, $U_0 = 8E_r$.

In this paper, we have theoretically and experimentally studied the implementation of a large momentum beamsplitter in an atomic interferometer. It is possible to realize a separation of 4 recoils between the 2 arms of the interferometer within 500 $\mu$s. The main issue to take care of is the light shift which degrades strongly the contrast of the fringes. Our proposal allows us to reduce this effect by a factor of 10 and finally permits us to realize an interferometer with a separation of 10 recoils between the two arms. A gain of a factor 4 in the resolution compared to a usual interferometer has been observed. This method seems to be very promising for the realization of a beam splitter with a separation of several tens of recoil velocities. The effect due to light shifts has been reduced by accelerating successively both arms of the interferometer. A way to suppress it systematically would be to accelerate both arms on the interferometer simultaneously (instead of doing it successively) by applying two counter-propagating accelerated lattices. In this case light shift would be completely suppressed. In the future, we plan to combine this kind of LMT beam splitter with Bloch oscillations between the two pairs of $\pi/2$ pulses [6] to realize a new measurement of the recoil velocity and therefore improve the determination of the fine structure constant.

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Note added: A similar experiment using BO to improve the sensitivity of atom interferometry has been recently performed at Stanford University [19].

[20] The second LMT pulse do not fully compensate the phase...
shift of the first one, because during the second LMT pulse, the two arms of the interferometer are initially separated by more than 2 recoils and therefore are loaded in different bands compared to the first LMT pulse.