Experimental Observation of the Suppression of the Dephasing in a Floquet Engineering Optical Lattice Clock

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Abstract: Accurately manipulating quantum states is a fundamental strategy for improving the performance of quantum metrology, computing, and simulation. However, the quantum state is susceptible to dephasing due to the temperature and density of the atomic ensembles. In this paper, we experimentally study the effect of Floquet engineering (FE) on the dephasing process in an $^{87}$Sr optical clock. By measuring the Rabi flopping process under different temperatures of the cold ensemble and numbers of atoms trapped in the lattice, our results show that the FE can suppress the dephasing due to high temperatures or a large number of atoms. Indeed, when the temperature and the number of atoms are 3.8 µK and 6300, respectively, the FE can obviously suppress the dephasing effect and improve the maximum excitation fraction of the Rabi spectrum by 15.4%.

Keywords: Floquet engineering; optical lattice clocks; strontium atoms; optical lattices

1. Introduction

Research on atomic clocks based on optical transitions is making rapid and steady progress. Recent advances in the frequency uncertainties of the state-of-the-art optical clocks have reached a $10^{-18}$ regime [1], which is deemed as suitable for the redefinition of SI a second in the future [2]. Laboratories around the world are working continually on improving the performance of optical clocks for SI-traceable measurements [3], improved timekeeping and global navigation satellite systems [4], geodesy measurements [1], cold-atom instruments for space applications [5,6], high precision tests of fundamental laws of physics including violations of relativity [7], and so on. The quest for ever-increasing measurement accuracy requires optical clocks to improve constantly with more elaborate manipulation of atomic systems. Precise manipulation of quantum systems is, at the same time, the preparation and subsequent tool for many quantum experiments, such as quantum sensing, quantum computing, and simulation. Floquet engineering (FE) is a common tool for steering quantum states [8,9] and has been employed in the optical lattice. In previous work, we have obtained a series of Rabi spectroscopy processes by periodically modulating the lattice trapping potential with a tool of FE [10]. Interference between the two Floquet channels was observed by simultaneously modulating the frequency of the lattice laser and the Rabi frequency [11]. The suppression of broadening of the Rabi spectrum by tunneling effects was also observed in the shallow potential FE lattice [12].

The $^{87}$Sr optical lattice clock (OLC) based on a highly forbidden $5s^21S_0 \rightarrow 5s5p \, ^3P_0 (F = 9/2)$ electric dipole transition is one of the most reported OLC and has realized the systematic uncertainty of $2 \times 10^{-18}$ and the best frequency instability of $2 \times 10^{-18} (\tau/s)^{-0.5}$ [2]. The dephasing of the Rabi flopping process indicates that the maximum excitation fraction is reduced exponentially with increasing clock laser pulse duration [13]. The dephasing process limits the clock detection time and, thus, affects the instability and uncertainty [14]. It has been observed that the dephasing effect is aggravated by increasing the temperature of the cold ensemble or the atomic density [15,16]. However,
improving the instability requires an increase in the number of atoms in lattice and a reduction in the preparation time of cooled atoms, which contradicts with the lower temperature as a lower temperature needs more time for cooling. Many efforts have been made to settle the contradiction between atomic interaction and clock performance in OLCs, such as by using the three-dimensional optical lattice [17], an atomic-array optical clock [18], and the cavity-enhanced lattice with a larger waist diameter [19]. In addition, dephasing is also one of the major challenges in many quantum sciences, such as quantum communication [20] and quantum information processing [21]. However, there are few reports about the suppression of the dephasing of the Rabi flopping process caused by the atomic thermal distribution over motional quantum states.

In this paper, we designed a scheme for experimentally verifying the suppression of dephasing in the OLC by the FE. We apply the FE to a dynamically driving many-body system and study experimentally the effect of FE on the excitation fraction of clock transition spectroscopy. We measure the excitation fraction of the Rabi spectrum as a function of clock pulse duration at different atomic densities and temperatures, with and without FE.

2. Experimental Apparatus

The details of the $^{87}$Sr OLC setup in our experiment have been described in previous work [22–24]. Here, we briefly recapitulate some basic parts and key improvements of the apparatus. The setup for the optical lattice trap and clock transition detection is shown in Figure 1a, and the partial level scheme of $^{87}$Sr is shown in Figure 1b. The strontium atoms in the oven are heated to 770 K to produce atomic flux, and then collimated with a 461 nm collimating beam (with a red frequency detuning of 15 MHz from the $5s^2\,1\,S_0^1 (F = 9/2) \rightarrow 5s5p \,3\,P_1^0 (F = 11/2)$ transition shown in Figure 1b) to reduce the transverse divergence angle. Before the magneto-optical trap (MOT), a Zeeman slower is used to increase the number of atoms with a velocity below 50 m/s. The first stage of cooling (blue MOT) is based on the $5s^2\,1\,S_0^1 (F = 9/2) \rightarrow 5s5p \,3\,P_1^0 (F = 11/2)$ transition with a red frequency detuning of 35 MHz. The large scatter rate of $2\pi \times 32$ MHz leads to atomic temperature of 2 mK after the blue MOT. For further cooling of the atoms to $\sim\mu$K, the second stage of cooling (red MOT) based on $5s^2\,1\,S_0^1 (F = 9/2) \rightarrow 5s5p \,3\,P_1^0 (F = 11/2)$ transition at 689 nm is applied. After two stages of cooling, roughly $10^8$ atoms are trapped in the red MOT with a temperature of 3 $\mu$K. The number of atoms trapped in the red MOT can be controlled by changing the power or frequency of the collimating beam without changing the atomic temperature.

At the end of the red MOT, the magnetic field for the MOT and all the cooling lasers are switched off, and the cooled atoms are automatically loaded into a one-dimensional horizontal optical lattice trap. The lattice beam with the “magic wavelength” of 813.42 nm has a maximum one-way power of 450 mW and is focused on the center of the red MOT with a waist radius of 50 $\mu$m, which corresponds to a trap depth of $U = 107 \, E_R$ ($E_R$ is the lattice photon recoil energy) [13]. Then, atoms are polarized to the Zeeman level of $m_F = \pm 9/2$ ($m_F = \pm 9/2$) by the $\sigma^+ (\sigma^-)$ polarized light corresponding to $5s^2\,1\,S_0^1 (F = 9/2) \rightarrow 5s5p \,3\,P_1^0 (F = 9/2)$ transition at 689 nm. At the spin-polarized stage, using three pairs of Helmholtz coils, the residual magnetic fields in the horizontal direction are compensated to near zero and the magnitude of the vertical magnetic field is about 50 mG to define the quantum axis along the vertical (gravitational) direction. Then, the energy filtering process is used to remove hot atoms by ramping down the lattice depth from 107 $E_R$ to 58 $E_R$ within 15 ms, holding for 20 ms, and ramping back to 107 $E_R$ within 15 ms [25]. The energy filtering stage allows us to control the temperature of the atoms trapped in the lattice by changing the magnitude of the lowest trap depth.

After completing the preparation of the cold ensemble, the clock laser with 698 nm is used to detect the transition probability of the $5s^2\,1\,S_0^1 (m_F = \pm 9/2) \rightarrow 5s5p \,3\,P_0^3 (m_F = \pm 9/2)$ clock transition. The clock laser frequency is stabilized on a 20 cm long ultralow-expansion (ULE) cavity via the Pound–Drever–Hall method. The clock laser beam used for frequency stabilization passes through an acoustic optical modulator (AOM). The power of the locking
The misalignment angle of 13 mrad is constant in all measurements. The atomic temperature of clock pulse duration at different atomic densities and temperatures, with and without dephasing in the OLC by the FE. We apply the FE to a dynamically driving many-body system and study experimentally the effect of FE on the excitation fraction of clock transition detection, the excitation fraction is measured using the “electronic shelved” method [26]. For suppressing the fluctuation of excitation caused by the changing of the number of total atoms, three 461 nm laser pulses with a duration of 2 ms are used to detect the numbers of atoms in the ground state \(N_g\), the excited state \(N_e\), and the background noise \(N_{bac}\), respectively. The normalized excitation fraction is expressed by \((N_e - N_{bac})/(N_e + N_g - 2N_{bac})\).

![Figure 1](image-url)  
Figure 1. Experimental setup for an optical lattice trap and clock transition detection and energy level scheme of the \(^{87}\)Sr atom. (a) A horizontal one-dimensional optical lattice potential is formed by overlapping the incident lattice beam and its reflection using a concave mirror (CM). The lattice light is generated by the 813 nm semiconductor laser with a tapered amplifier. The amplitude of the radio frequency signal for the acoustic optical modulator (AOM) is controlled through a voltage-controlled attenuator (VVA). The Floquet engineering (FE) is realized by applying a sinusoidal voltage to the piezoelectric (PZT) of the lattice laser. The frequency of the 698 nm clock laser is stabilized to an ultralow-expansion (ULE) glass cavity. A photomultiplier (PMT) is used to collect the fluorescence emitted by the atoms. (b) Energy level scheme of the \(^{87}\)Sr atoms.

The FE is realized in OLC by modulating the lattice frequency via applying a sinusoidal voltage signal to the piezoelectric (PZT) of the 813 nm external cavity diode laser. In a previous work, we experimentally demonstrated that the Floquet quasi-energy bands are generated by the dynamical periodic modulation of the incident lattice laser frequency [10]. As the FE is applied, the lattice frequency can be expressed by \(\omega_L = \bar{\omega}_L + \omega_a \sin(\omega_k t)\), where \(\bar{\omega}_L\) is the average frequency of lattice light, \(\omega_k\) indicates the modulation frequency, and \(\omega_a\) represents the modulation amplitude. With FE, the ground and excited states will split to a series of Floquet quasi-levels with a frequency gap of \(\omega_k\). The number and intensity of Floquet sidebands are controlled by the normalized driving amplitude \(A = \omega_a \omega_p L/2\bar{\omega}_L C\), where \(\omega_p\) is the frequency of clock laser and the distance between cooled atoms and reflecting-mirror of lattice beam is \(L \approx 30\) cm [10].

3. Experimental Observation of Rabi Spectroscopy and Dephasing

3.1. Sideband-Resolved Spectroscopy and High-Resolution Rabi Spectroscopy

The inhomogeneity excitation, which causes the dephasing of the Rabi flopping process, originates from the thermal distribution of atoms on external states, the atomic interaction, and the misalignment angle between the clock beam and the lattice beam [13,15,16]. The misalignment angle of 13 mrad is constant in all measurements. The atomic temperature can be measured by the sideband-resolved spectroscopy shown in Figure 2. Herein,
the red squares correspond to atoms in the lattice loaded directly from the red MOT, and the blue triangles indicate the loading with an energy filtering process. The longitudinal trap frequency is \( \nu_z \approx 71 \text{ kHz} \) inferred from the frequency gap between the sharp edge of the blue sideband and the carrier. By calculating the ratio of the integrated absorption cross sections of the red and blue sidebands, the longitudinal temperature with and without the energy filtering process is determined to be \( T_{11} \approx 3.8 \mu K \) and \( T_L \approx 2.3 \mu K \), respectively.

![Figure 2](image)

**Figure 2.** Sideband-resolved spectroscopy. Red open squares and blue open triangles represent the cases without and with energy filtering process, respectively. The solid lines are the combinations of fits to the carrier, the red sideband (red sb.) and the blue sideband (blue sb.) according to reference \[13\]. The longitudinal temperatures of the red squares and blue triangles are \( T_{11} \approx 3.8 \mu K \) and \( T_L \approx 2.3 \mu K \), respectively.

To carefully study the dephasing of the Rabi flopping process with and without FE, the high-resolution Rabi spectrum is needed, as shown in Figure 3, in which the excitation fraction depends on the duration of the clock pulse and the effective coupling strength. Figure 3a shows the high-resolution Rabi spectrum without FE, where only one peak is observed corresponding to the \( ^1S_0 \rightarrow ^3P_0 \) transition. With FE, the \( ^1S_0 \) and \( ^3P_0 \) states split into a series of Floquet quasi-levels, which leads to multiple transition peaks. The number of peaks and the corresponding excitation fraction of each peak with FE are determined only by the driven amplitude \( A \), and the frequency gap between adjacent peaks equals the driven frequency \( \omega_s/2\pi \). As \( A \approx 0.72 \) and \( \omega_s/2\pi = 100 \text{ Hz} \), the FE Rabi spectrum is shown in Figure 3b, where the carrier and the first-order Floquet sidebands have the same amplitude. Without considering the interaction between atoms and the tunneling effect between lattice sites, the FE spectrum can be obtained by solving the effective Hamiltonian \[10\], as follows:

\[
H_{nz,nr}(t) = \frac{\hbar}{2} \left( \delta + \omega_a \cos(\omega_a t) \right) \sigma_{nz,nr}^{(3)} + \frac{\hbar \Omega_{nz,nr}}{2} \sigma_{nz,nr}^{(1)},
\]

where \( \sigma_{nz,nr}^{(1)} \) and \( \sigma_{nz,nr}^{(3)} \) are Pauli matrices, while \( nz \) and \( nr \) indicate the longitudinal and transverse motional quantum numbers of the atoms, respectively. Additionally, \( \delta = \omega_c - \omega_p \) is the detuning (\( \omega_c \) is the resonance frequency of the clock transition), while \( \Omega_{nz,nr} = \Omega e^{-(\eta_z^2 + \eta_r^2)/2} L_{n_z}(\eta_z^2) L_{n_r}(\eta_r^2) \) is the modified coupling strength of probe light to the clock transition in the external states \( n_z, n_r \), where \( \eta_z \) and \( \eta_r \) are the longitudinal and transverse Lamb–Dicke parameters, respectively \[13\]. Herein, \( L_n(\cdot) \) is the 0th order generalized Laguerre polynomial and \( \Omega \) is the bare state coupling strength (without FE) extracted from the Rabi oscillation.
interaction between atoms and the clock laser will be reduced with FE compared with the absence of FE. Based on the high-resolution Rabi spectra, we measure the excitation fraction at different clock pulse durations. When the resolved sideband approximation holds \( \Omega_{n_1,n_2} |J_n(M)| \ll \omega_s \) (the largest \( \Omega_{n_1,n_2} \) is less than \( 5 \times 2\pi \) Hz, but the \( \omega_s \) is \( 100 \times 2\pi \) Hz in this experiment), the coupling strength between the clock laser and atoms of the nth Floquet sideband can be expressed by \( \frac{\Omega}{|\Delta|} \mathcal{J}[2A] \), where \( J_n[-] \) is the Bessel function of the first kind [10].

### 3.2. Suppression of the Dephasing of the Rabi Flopping Process

If the clock laser intensity keeps constant, the above analysis indicates that the coupling strength between atoms and the clock laser will be reduced with FE compared with the case of the absence of FE. This will hamper the measurement of the dephasing suppression of the Rabi flopping process by FE, as the lower coupling strength indicates the longer clock pulse duration to reach the maximum excitation fraction, and the inhomogeneous excitation will lead to additional dephasing of the Rabi flopping process. Thus, the clock laser intensity is different between FE and the absence of FE. Based on the high-resolution Rabi spectra, we measure the excitation fraction at different clock pulse durations with and without FE, as shown in Figure 4. Herein, the driving amplitude of \( A = 0.72 \) is optionally chosen, as we found that changing the driving amplitude from 0.4 to 1.5 will not lead to obvious variation to the Rabi flopping process. The coupling strengths of the carrier (corresponding to the 0th sideband shown in Figure 3) are about 4.1 Hz in Figure 4 to avoid extra dephasing induced by inhomogeneous excitation. In this experiment, we carefully study the suppression of the dephasing by FE while considering two possible factors of interaction between atoms and the temperature of the cold ensemble. The strength of the interaction between atoms is proportional to the number of atoms, which is inferred from the atomic detection noise [27].

Figure 4a shows the excitation fraction as a function of clock pulse duration under three experimental conditions without FE. Obviously, both parameters of temperature and atomic interaction will lead to dephasing of the Rabi flopping process. The interaction between atoms causes the phenomenon of dephasing due to the following three aspects: the density-dependent frequency shift is different between lattice sites due to the Gaussian distribution of atoms [28]; the density shift in a lattice site is different for atoms populated...
in different longitudinal and transverse motional quantum numbers \( n_z \) and \( n_r \) [16]; the inelastic e-e collision causes the loss of excited atoms [15]. The temperature of the cold ensemble determines the distribution of atoms in the motional quantum states, and the higher temperature will lead to more populations in higher motional quantum states, which aggravates the dephasing of the Rabi flopping process [13].

Holding the number of atoms on \( N_L = 2100 \), the influence of the atomic temperature on the dephasing is studied by measuring the Rabi flopping processes without and with FE at low and high temperatures of \( T_L = 2.3 \) \( \mu \)K and \( T_H = 3.8 \) \( \mu \)K, respectively, shown in Figure 4b,c. To study the influence of the atomic interaction on the dephasing, keeping the temperature of the cold ensemble of \( T_H = 3.8 \) \( \mu \)K, the Rabi flopping processes with and without FE are measured under low and high atomic density (with the numbers of atoms of \( N_L = 2100 \) and \( N_H = 6300 \), respectively), as shown in Figure 4c,d. Figure 4c,d demonstrate that the excitation fractions with FE are higher than the case without FE, indicating that the dephasing of Rabi flopping process caused by high temperature and atomic interaction can be suppressed using FE. With FE, the percentages of the maximum excitation fraction in Figure 4c,d increase by 7.7% and 15.4%, respectively. Obviously, the results shown in Figure 4c,d confirm that FE can suppress the dephasing. This shows that the FE can simultaneously suppress the dephasing caused by the thermal distribution of atoms and the atomic interaction. However, Figure 4b shows almost the same excitation fraction, which indicates the FE cannot obviously further reduce the dephasing as there are weak atomic interactions and the low temperature of the cold ensemble.

**Figure 4.** Rabi flopping process of the carrier as a function of the clock laser pulse duration. In all figures, the points are experimental measurements, the solid curves indicate fitting according to reference [13], and \( T_H = 3.8 \) \( \mu \)K, \( T_L = 2.3 \) \( \mu \)K, \( N_H = 6300 \), and \( N_L = 2100 \). (a) Measurements under three pairs of experimental parameters without FE. (b) In the parameters of \( T_L \) and \( N_L \), the measurements without FE (black squares) and measurements with FE (red circles) are presented. (c) In the case of the \( T_H \) and \( N_L \) samples, measurements without FE (black squares) and measurements with FE (red circles) are presented. (d) In the case of \( T_H \) and \( N_H \) atomic samples, measurements without FE (black squares) and measurements with FE (red circles) are presented. All measurements with FE hold the parameters of \( A = 0.72 \), and \( v_0 = 100 \) Hz, and correspond to the excitation fraction of the carrier of the FE spectrum.
4. Conclusions

We measured the Rabi flopping process without and with FE under three groups of parameters of $T_L = 2.3 \, \mu K, N_L = 2100, T_H = 3.8 \, \mu K$ and $N_L = 2100, T_H = 3.8 \, \mu K$ and $N_H = 6300$, respectively. The excitation fractions in several comparative experiments show that the FE in OLC can suppress the dephasing of the Rabi flopping process caused by high temperature and atomic density. With the parameters of $T_H = 3.8 \, \mu K$ and $N_H = 6300$, the maximum excitation fraction with FE is improved by a relative proportion of 15.4% compared with the case of the absence of FE. This suppression makes FE a potential tool for preparing high-fidelity quantum states in some complex quantum systems where decoherence is evident. Although there is a lack of theory to support our observations, the experimental results show the potential of plentiful physics in FE-based OLC. Our previous publication has demonstrated the advantage of FE-based OLC in the realization of shallow lattices for space. This work shows another advantage of the potential of higher instability and relaxation of the atomic temperature in FE-based OLC. This periodical modulation inaugurates a novel potential scheme for applying long-time light–atom interactions in dynamically driven many-body systems, which has broad applications in quantum metrology [29] and quantum computing [30].

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