Abstract: S3.00010 : Coherent control of Wannier-Stark states via interference between one- and two-phonon excitation

We demonstrate that the control of quantum vibrational states in an optical lattice may be achieved by using interference between two-phonon excitation at $\omega$ and one-phonon excitation at $2\omega$. We use this technique to improve the ratio of coherent coupling to loss in our system. In our experiment, $^{85}\text{Rb}$ atoms are trapped in a vertical optical lattice, leading to a tilted-washboard potential when the effect of gravity is considered. While neighboring Wannier-Stark states may be coherently coupled by sinusoidal drive of the lattice displacement at the secular frequency $\omega$, this also leads to leakage into higher excited states and eventual loss from the lattice. We use coherent control to mitigate this problem, by adding a simultaneous parametric drive at $2\omega$, directly coupling states of the same parity. The resonant drive corresponds to Raman scattering of laser beams phase-modulated (PM) at $\omega$, while the parametric drive corresponds to Raman scattering of laser beams amplitude-modulated (AM) at $2\omega$. We demonstrate experimentally that quantum interference between the absorption of two PM quanta and one AM quantum can be used to control the branching ratio, and specifically, to improve the ratio of coherent coupling to loss.
Coherent control of Wannier-Stark states via interference between one- and two-phonon excitation

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Motivation

- Optical lattices are a leading candidate system for quantum information processing
- Lattices are also an important arena for studying condensed-matter and many-body phenomena
- Coherent control of a two level system with a decay channel is still an important topic related to decoherence in quantum information processing
Experiment Control of Lattice Beams

Tilted-washboard Potential and Wannier-Stark states

State Preparation and Measurement

85Rb laser cooled to 10µK
10^{10} atoms/cm^3

Optical Lattice:
25GHz detuned to D2 line, intensity around 7mW/mm^2
lattice depth around 20E_r, scattering rate around 60ms
lattice constant around 0.93µm
10^5 atoms/plane
The vertical optical lattice plus the gravity in -x direction, form a tilted wash-board potential

The motion part Hamiltonian for a single atom in this wash-board potential is,

\[ H = \frac{p^2}{2m} + U(x) \]

where, \[ U(x) = U_0 \sin^2 kx + mgx \]

It’s known the eigenstates of this Hamiltonian are the Wannier-Stark states.
State Preparation and Measurement

- **Initial Lattice**
- **After adiabatic decrease**
- **Ground State**
- **1st Excited State**

**Well Depth**

- **0**
- **t (ms)**
- **t₁**
- **t₁+40ms**

**Operations**

- **2 bound states**
- **1 bound state**

**Preparation**

- **Ground State (P₀)**
- **1st Excited State (P₁)**
- **Lost Atoms (P_{Loss})**
Phase Modulation v.s. Amplitude Modulation

**Transition due to PM: two-phonon excitation**

**Transition due to AM: one-phonon excitation**

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One-phonon v.s. Two-phonon

\[ \theta = \phi_{AM} - 2\phi_{PM} \]

One-phonon v.s. Two-phonon

Experiment results, AM loss around 10%

\[ \theta = \phi_{\text{AM}} - 2\phi_{\text{PM}} \]

\[ \phi = \phi_{\text{AM}} = 15^\circ \]

\[ \phi = 0^\circ \]

One-phonon v.s. Two-phonon interference
Effects of decoherence

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Simulation

Experiment results, AM loss around 10%

Simulation with 18-recoil flat lattice

\[ H(t) = \frac{p^2}{2} + [1 + \eta(t)] r \sin^2 (x + \phi(t)); \]

- Inhomogeneous broadening
- Gravity
one- and two- phonon interference

\[
\sqrt{\text{Loss}_{AM+PM}} = \sqrt{\text{Loss}_{AM}} + e^{i\theta} \sqrt{\text{Loss}_{PM}}
\]

Constructive: \[\text{Loss}_{AM+PM} = \text{Loss}_{AM} + \text{Loss}_{PM} + 2\sqrt{\text{Loss}_{AM} \times \text{Loss}_{PM}}\]

Destructive: \[\text{Loss}_{AM+PM} = \text{Loss}_{AM} + \text{Loss}_{PM} - 2\sqrt{\text{Loss}_{AM} \times \text{Loss}_{PM}}\]

No interference: \[\text{Loss}_{AM+PM} = \text{Loss}_{AM} + \text{Loss}_{PM}\]

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one- and two-phonon interference

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\( \phi_{PM} = 15^\circ \)

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one- and two-phonon interference

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one- and two-phonon interference

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Coherent Control
one- and two-phonon interference

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one- and two-phonon interference

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Coherent Control
Effects of decoherence

$$\phi_{PM} = 10^\circ, \eta_{AM} = 30\%$$

![Graph showing population over time for ground state, first excited state, and loss](image-url)
Conclusion

- Coherent control of Wannier-Stark states via interference between one-2$\omega$-phonon and two-$\omega$-phonon
- Use this technique to reduce the coupling into the lossy states
- This technique may be used as a method of detecting decoherence of the system
- Better parameters to be found
- Pulse engineering technique of quantum control, such as, GRAPE

Thank You!!
S.H.O. Approximation

\[ U(x) \approx U_0 k^2 x^2 \]

Wannier–Stark states
Squeezed coherent state

Displacement and Squeezing

Theoretical max overlap of ground state and a coherent state is \( P_{1st} = \frac{1}{e} \)
Theoretical max overlap of ground state and a squeezed coherent state is \( P_{1st} = \frac{3\sqrt{3}}{4e} \)
Displaced squeeze state simulation

For PM $\phi_{pk-pk} \approx \frac{1}{60} a$ and AM $\eta_{pk-pk} \approx 17.5\% U_0$ (pulses given below), it happens at $t = 4T_{\text{res}}$. 

Overlap with Fock states

- Green: ground state
- Blue: first excited state
- Red: all other states
- Dashed line: theoretical max

Displacement of potential

Squeeze of potential

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Simulation for long time

Simulation of AM and PM in a flat lattice:

AM 30% 8cycle 100µs PM 10° 4cycle 200µs for 18−recoil Lattice

AM delayed after PM (µs)

Band n = 1 AM + PM
Band n = 2 AM + PM
The rest AM + PM
Band n = 1 PM only
Band n = 2 PM only
The rest PM only
Band n = 1 AM only
Band n = 2 AM only
The rest AM only