Observing the Polarization Dependent Light Shifts Using an Atom Fountain

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Abstract. We theoretically predicted and experimentally demonstrated the sinusoidal shifts of the $^{87}$Rb atom Raman transition frequencies as the polarization vectors of the Raman lasers rotate. We also presented the vanish of the differential light shifts for the magnetic sensitive Raman transitions at some elliptically polarized configurations while no vanish for the magnetic insensitive Raman transition. These results are helpful for the evaluation and elimination of the light shifts induced systemic errors in the atomic magnetometer, atomic interferometer, atomic clock and quantum computing.

1. Introduction

Light shifts (LSs) were first discovered in 1960s [1], which refers to the alteration of the atomic energy levels due to the external oscillatory electric fields and plays a fundamental role in a vast variety of physical applications ranging from basic atomic physics [2] to applied quantum registers [3], quantum computing [4], atomic magnetometers [5], atomic clocks [6] and atomic interferometers [7]. In particular, for atom interferometry in a warm vapor [8] and quantum memory with a photonic polarization qubit [9], the LSs are significant because either the Raman laser Rabi frequency is up to 1.2 MHz or the Zeeman sublevels other than the clock states are employed. To date, the research on LSs mainly focuses on two aspects. On one hand, it’s about methods to calculate [10, 11], measure [12-14] and eliminate [15, 16] the adverse effects of the LSs that reduce the fidelity and accuracy of the experiments. These methods include hyper-Ramsey schemes [17], magic wavelength lattices [18], and intensity ratio of the lasers [19]. On the other hand, it’s about making use of the LSs to achieve sensitive measurement such as absolute polarization [20] and optical potential [21], to cancel some effects such as Zeeman effects [22], and to achieve new physical such as photon-echo [23].

This Letter aims to study the effect of laser polarization on the differential light shifts (DLSs) of the $^{87}$Rb atom Raman transitions in near-resonant case, and demonstrate the vanish of the DLSs in elliptically polarized laser configurations. These results are helpful for the evaluation and elimination of
the light shifts related systemic errors in the atomic magnetometer, atomic interferometer, atomic clock and quantum computing.

2. Theoretical model

According to the electric-dipole selection rules, the π transitions are forbidden and only the σ transitions are allowed when a quantization magnetic field parallel to the propagation direction of the Raman beams is applied. Assuming the atoms are distributed evenly among the magnetic sublevels of the $F = 2$ hyperfine states, only seven transitions with $\Delta F = 1$ and $\Delta m_F = 0, \pm 2$ will happen considering arbitrarily polarized lasers are composed of the left and right circularly polarized lasers. Figure 1(a) depicts these transitions in the presence of Zeeman shifts and light shifts. The frequency differences of the two lasers driving the Raman transitions satisfy

$$
\Delta E_{F,m_F}^{\text{ac}} = -\alpha_{F,m_F}(\omega) \left( \frac{\epsilon}{2} \right)^2,
$$

and the dynamic polarizability $\alpha_{F,m_F}(\omega)$ is composed of

$$
\alpha_{F,m_F}(\omega) = \alpha_F^{(s)}(\omega) + (\hat{k} \cdot \hat{B}_e) \frac{m_F}{2F} \alpha_F^{(v)}(\omega) + \left( 3 \hat{\zeta} \cdot \hat{B}_e \right)^2 \left( 1 - \frac{3m_F}{2F} \left( F+1 \right) - \frac{2F}{2F-1} \alpha_F^{(t)}(\omega) \right),
$$

where the $m_F$ independent factors $\alpha_F^{(s)}(\omega)$, $\alpha_F^{(v)}(\omega)$ and $\alpha_F^{(t)}(\omega)$ are named as scalar, vector and tensor polarizabilities, respectively.

![Figure 1](attachment:figure1.png)

Figure 1. Schematic diagram of the theoretical model and setup. (a) The selection rules allowed $^{87}$Rb atom D2 line Raman transitions. (b) The resultant magnetic field vector $\vec{B}_e$ and the Raman laser complex polarization vector $\hat{\zeta}$ in a Cartesian coordinate. (c) The atomic fountain experimental setup.
xoy plane and \( \hat{z} \) (the x-axis), respectively. The complex polarization unit vector \( \hat{z} \) can be expressed as

\[
\hat{z} = e^{i\gamma} \left( \cos \phi \hat{e}_{\text{maj}} + \sin \phi \hat{e}_{\text{min}} \right),
\]

in which \( \gamma \) is a real number, the unit vectors \( \hat{e}_{\text{maj}} \) and \( \hat{e}_{\text{min}} \) (\( \hat{e}_{\text{maj}} \times \hat{e}_{\text{min}} = \hat{k} \)) align with the semi-major-axis and semi-minor-axis of the ellipse which swept out by the tip of the electric field vector of the laser in one period, respectively [10]. The parameter \( \phi \), represents in the \( \hat{z}_{\text{maj}} - \hat{z}_{\text{min}} \) plane, is related to the degree of circular polarization with \( \phi = \sin 2\phi \).

Figure 1(c) depicts the experimental setup and a detailed description of the whole system can be found in Refs. [25, 26]. The intensity ratio and relative frequency of the two Raman beams are determined by the 0th to +1th sideband of a fiber electro-optical modulator (FEOM). The frequencies of the two Raman lasers are red shifted 162 MHz to the \( F = 2 \rightarrow F’ = 1 \) transition frequency by a double-pass optical path using an acoustic optical modulator (AOM), which also serves as the switch and intensity controller of the Raman beams. The Raman beams coming from a polarization maintaining (PM) fiber are purified to linear polarization with a quarter wave plate (QP) firstly, and are adjusted to arbitrary polarization with a half wave plate (HP) and a polarization beam splitter (PBS) afterwards. According to the principles of optics [27, 28], as the fast-axis of the QP rotates an angle \( \theta \) with the x-axis, the semi-major-axis \( \hat{z}_{\text{maj}} \) of the polarization ellipse rotates along with \( \theta \), the axis angle \( \beta \) of the complex polarization vector rotates 2 times of \( \theta \), and the ellipticity angle \( \phi \) is related to \( \theta \) by \( \sin 2\phi = -\sin 2\theta \).

With above knowledge, the dynamic polarizability Eq. (3) applied to the Zeeman sublevels of the two ground states are simplified to

\[
\alpha_{i,m_j}(\omega) = \alpha_i^0(\omega) - \cos \theta_j \sin 2\theta_j \left[ \frac{m_{j1}}{2} \alpha_i^{x1}(\omega) + \left[ 3 \cos^2 \theta_j - 1 \right] \frac{3m_{j1}^2 - 2}{2} \alpha_i^y(\omega) \right],
\]

\[
\alpha_{i,m_j}(\omega) = \alpha_i^x(\omega) - \cos \theta_j \sin 2\theta_j \left[ \frac{m_{j2}}{4} \alpha_i^{x2}(\omega) + \left[ 3 \cos^2 \theta_j - 1 \right] \frac{3m_{j2}^2 - 6}{12} \alpha_i^y(\omega) \right],
\]

where \( m_{j1} = 0, \pm 1 \) and \( m_{j2} = 0, \pm 1, \pm 2 \). Noting the amplitude of the laser field \( E_i(\omega_i) \) as \( \epsilon_i \), the intensity ratio between the two Raman lasers is \( R = (I_2/I_1 = 3:1 \text{ here}) \), and taking the polarizabilities \( \alpha_i^f(\omega_2) \) calculated in our previous work [24], in which \( l = S, V, T \) represent the scalar, vector and tensor components, \( F = 1, 2 \) represent the two ground state hyperfine levels, \( j = 1, 2 \) represent the two Raman beams, the DLSs of \( |F = 2, m_{j2} \rangle \rightarrow |F = 1, m_{j1} \rangle \) transitions are composed of the differential scalar light shifts (DSLs), differential vector light shifts (DVLs) and differential tensor light shifts (DTLs) by

\[
\Delta E^w = \Delta E^s + \Delta E^v + \Delta E^t =
\]

\[
- \left( \frac{\epsilon_i}{2} \right)^2 \left[ \left[ \alpha_{i,0}^z(\omega_1) + q\alpha_{i,0}^z(\omega_2) \right] - \left[ \alpha_{i,0}^z(\omega_1) + q\alpha_{i,0}^z(\omega_2) \right] \right] \left[ \alpha_{i,0}^y(\omega_1) + q\alpha_{i,0}^y(\omega_2) \right] \left[ \alpha_{i,0}^y(\omega_1) + q\alpha_{i,0}^y(\omega_2) \right] \left[ \alpha_{i,0}^y(\omega_1) + q\alpha_{i,0}^y(\omega_2) \right] - \left( \frac{\epsilon_i}{2} \right)^2 \left[ 3 \cos^2 \theta_j - 1 \right] \left[ \alpha_{i,0}^y(\omega_1) + q\alpha_{i,0}^y(\omega_2) \right] \left[ \alpha_{i,0}^y(\omega_1) + q\alpha_{i,0}^y(\omega_2) \right] \left[ \alpha_{i,0}^y(\omega_1) + q\alpha_{i,0}^y(\omega_2) \right] - \left( \frac{\epsilon_i}{2} \right)^2 \left[ \alpha_{i,0}^y(\omega_1) + q\alpha_{i,0}^y(\omega_2) \right] \left[ \alpha_{i,0}^y(\omega_1) + q\alpha_{i,0}^y(\omega_2) \right] \left[ \alpha_{i,0}^y(\omega_1) + q\alpha_{i,0}^y(\omega_2) \right].
\]

3. Experimental setup and procedure

The sensor used for measuring the DLSs is developed based on the atomic fountain clock in Shanghai Institute of Optics and Fine Mechanics (SIOM), and its schematic diagram is shown in Figure 1(c). Here we only describe the major parameters related to this experiment. The intensity ratio and frequency difference of the two Raman beams are determined by the 0th to +1th sideband of a fiber electro-optical modulator (FEOM). The frequencies of the two Raman lasers are red shifted 162 MHz to the \( F = 2 \rightarrow F’ = 1 \) resonant frequency by a double-pass optical path using an acoustic optical modulator (AOM), which also serves as the switch and intensity controller of the Raman beams. The Raman beams coming from a polarization maintaining (PM) fiber are purified to linear polarizations with a half-wave
plate (HP) and a polarization beam splitter (PBS) firstly, and then are adjusted to arbitrary polarizations with a quarter-wave plate (QP).

In this experiment, about $10^8$ $^{87}$Rb atoms are trapped and cooled to 2.5 μK in the magneto-optical trap (MOT) chamber using a fold optical path [29] in 1 s, and then are launched vertically with a velocity of 4.188 m/s in 2 ms. The repumping laser is switched off 1 ms later than the cooling laser to ensure all atoms are in the $F = 2$ ground state. At 1.4 s, when the atoms reaching a launch height of 891 mm, a pair of co-propagating Raman beams with a Gaussian diameter of 16 mm and a duration time of 8 ms are injected from the bottom window in order to interact with atoms to create two photon Raman transition. When the atoms fall back through the detection zone, the atom population in the $F = 1$ and $F = 2$ levels are detected to give a transition probability. The relative frequency of the Raman beams is increased progressively at each launch-detection cycle by modulating the FEOM to generate a Raman transition spectrum. The above processes are repeated with four laser intensities (9.54, 19.18, 31.95, 47.31 μW/cm²) firstly and also repeated with 25 sets of QP angles (0°, 15°, 30°, ..., 345°, 360°) afterwards in order to examine the effects of the laser intensity and polarization on the Raman transition frequencies.

4. Results
The dependences of $\omega_{-1,-1}$, $\omega_{0,0}$ and $\omega_{1,1}$ on the rotation angle $\theta$ of the QP are depicted in Figure 2 (a) as Blue diamonds, Red circles and Magenta triangles connected by dashed lines, respectively. The green squares (noted as $\omega_{\pm 1, \mp 1}$) represent the transition frequencies of $|2, 1\rangle \rightarrow |1, -1\rangle$ and $|2, -1\rangle \rightarrow |1, 1\rangle$ in the Lin-Lin configuration ($\theta = k \times 90^\circ$, $k = 0, 1, 2, 3, 4$), in which situation the $|2, 0\rangle \rightarrow |1, 0\rangle$ transition is forbidden. The solid lines are the theoretically calculated Raman transition frequencies using Eq. (1)-(6). In this calculation, the first-order Zeeman shifts on $\omega_{-1,-1}$ and $\omega_{1,1}$ are calculated as $\mp 1103.75$ Hz (the absolute magnetic field is determined using the method proposed in Ref. [30]), the Doppler shifts of the three resonant frequencies are calculated as 6.15 Hz at the Raman laser irradiation time of 1.4 s, the angles of $\theta_0$ and $\alpha_0$ are measured as 3.4° and 17.72° by probing the line strengths of the stimulated Raman transitions [26], and the Raman laser intensity is measured as 31.95 μW/cm² by detecting at the output port of the polarization maintaining fiber using a photon diode. The experimental results are in good agreement with the theoretical results, and both show the sinusoidal shift periods of $\omega_{-1,-1}$ and $\omega_{1,1}$ are approximately 180° while the shift period of $\omega_{0,0}$ is approximately 90°.

![Figure 2](image_url)

Figure 2. Schematic diagram of the polarization dependent light shifts. (a) The transition frequencies on the rotation angle $\theta$ of the quarter-wave plate. (b) Total effects of laser polarization and intensity on the differential light shifts of the Raman transition frequencies.

Figure 2(b) depicts the total effects of the laser polarization and intensity on the DLSs of the Raman transitions. Besides sinusoidal shifts with Raman laser polarization, the DLSs increase with laser
intensity. Furthermore, the vanish of the DLSs for $\omega_{a, a}$ and $\omega_{b, b}$ at some elliptically polarized configurations (marked as $P_1$ to $P_6$) are observed, which means the DVLSs and DTLSs cancel the DSLSs exactly. However, due to the absence of the DVLSs, the DLS for $\omega_{0, 0}$ doesn’t vanish at any Raman laser polarization configuration.

5. Conclusion

In conclusion, we have presented the polarization dependent DLSs and the vanish of the DLSs in the near-resonant $^{87}$Rb atom Raman transitions using a cold atomic fountain. Analytical theory has predicted that the transition frequencies of the magnetic sensitive and insensitive transitions would shift sinusoidally with periods of approximately 180° and 90° respectively, and the results have been confirmed experimentally. Furthermore, we observed the vanish of the DLSs for the magnetic sensitive Raman transitions at some elliptically polarized laser configurations while no vanish for the magnetic insensitive transition with our experimental parameters. These results are helpful for measuring and eliminating the Light shift related systemic errors in the atomic magnetometer, atomic clock, atomic interferometer and quantum computing. Furthermore, the scalar, vector and tensor components of the DLSs and the effective magnetic field vector can be extracted from the sinusoidal shifted transition frequencies.

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