Two-photon ac-Stark effect in Raman-Ramsey Interactions

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***Abstract*—For the two-photon ac Stark effect in Raman-Ramsey configuration, such as the Raman clock, and pulsed CPT clock configuration, an interference phenomenon of two-photon ac Stark effect is predicted. Here we report this new physical phenomenon, the interference of two-photon ac Stark effect in two-zone Raman-Ramsey interactions, which is general in any Raman-Ramsey spectroscopy. In particular, for an atomic beam Raman clock configuration, the ac Stark shift will present an interference fringe caused by the separated oscillatory-field interaction when the shift fields interact with atoms at two zones. On the center of dispersion shape of normal ac-Stark shift, an interference pattern appeared when the scale of frequency detuning is expanded.**

I. Introduction

Recently, the interference of ac Stark effect and ac Zeeman effect in the separated oscillatory-fields technique has been predicted theoretically [1-3] and the ac Zeeman interference effect has been demonstrated experimentally in a Cesium beam atomic clock system [4].

It has been pointed out clearly that, the interference of ac Stark effect and ac Zeeman effect is a general physical phenomenon in any Ramsey separated oscillatory-fields configuration [1-3], including in Ramsey-Borde atom interferometry [5].

But the above-mentioned works [1-4] are limited to single-photon transition. For the two-photon ac Stark effect in Raman-Ramsey configuration, such as the Raman clock [6-12] and pulsed CPT clock configuration [13-15], an interference phenomenon of two-photon ac Stark effect has never been addressed. Here we report this new physical phenomenon, the interference of two-photon ac Stark effect in two-zone Raman-Ramsey interactions, which is general in any Raman-Ramsey spectroscopy. In particular, for an atomic beam Raman clock configuration, the ac Stark shift will present an interference fringe caused by the separated oscillatory-field interaction when the shift fields interact with atoms at two zones.

We will present the result of numerical calculation of the interference of two-photon ac Stark effect of Raman-Ramsey configuration in a Cesium beam. By calculating density-matrix equations at two interaction zones and free-drift region, our results show an ac Stark interference pattern, composing of a normal two-photon Raman dispersion line shape and a Ramsey interference pattern, has a few oscillations near the resonant frequency caused by two-zone Raman-Ramsey interaction. Its physical origin is the interference of the two two-photon ac Stark effects in the two Ramsey regions. In a real atomic clock with Raman-Ramsey configuration, the laser spectral impurity, like the sidebands of modulated laser will cause ac Stark shifts at two regions of Ramsey separated fields and, these ac Stark shifts at two regions of Ramsey separated fields can interfere with each other.

II. Theoretical Analysis

Our calculations bear on the experimental configuration reported by Hemmer and his colleagues, we thus use the same notations as in [6], but we use the Cs atomic beam [12].

The two-photon transition in two-zone Raman interaction is illustrated schematically with the three-level atom in Fig.1(a). In Raman-Ramsey interaction with a Cesium beam [12], as shown in Fig.1(b), |1>and |3> are the $6\ ^2S_{1/2}(F=4)$ and $6\ ^2S_{1/2}(F=3)$ ground sublevels respectively, |2> the exciting state $6\ ^2P_{3/2}(F'=4)$. The two lasers, at angular frequencies of ω_1 and ω_2, are simultaneously on resonance with the intermediate state |2>. A and B stand for two interaction zones, γ_2 represents |2> state spontaneous decay rate.

Strictly speaking, the theoretical expression of ac Stark effect in [6] is not the Raman-Ramsey ac Stark effect. The reason is that the analytical expression of the ac Stark shift given by Eq. (6b) in [6] is only calculated in the zone A, thus it is a function of τ_A only. Therefore it is incomplete. As the analytical expression of observed fluorescence, the Eq. (6a) in [6] is calculated to include the effect due to the zone B, or say

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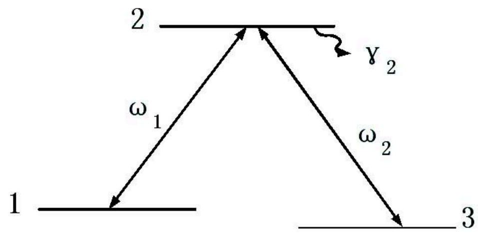
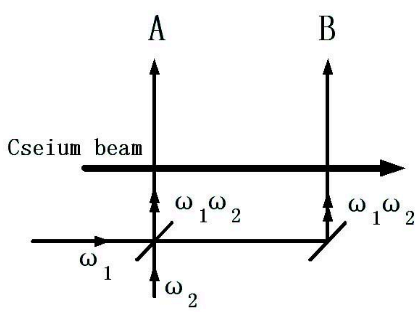
to include time of $\tau_A + T + \tau_B$. Thus it will be a function of τ_A, T, and $.\tau_B$. In our view, a complete expression of ac Stark shift in two-zone Raman-Ramsey interactions should also be a function of τ_A, T, and τ_B. A complete analytical expression of ac Stark shift in two-zone Raman-Ramsey interactions will appear elsewhere [16]. In this paper, we have calculated numerically the ac Stark shift to include the zone B. Naturally, our result is a function of parameters of τ_A, T, and τ_B.



(a)



(b)

Fig.1. (a) Schematic of stimulated resonance Raman interaction (b) Schematic of Raman-Ramsey transition setup.

To calculate the interference of the two-photon ac Stark shift in two-zone Raman–Ramsey interaction, we choose the time-dependent density-matrix equations to describe the fluorescence intensity and energy level shift. The relevant density-matrix equations in the interaction picture are:

$$\rho_{11}' = -(\tfrac{1}{2} i\Omega_1 \alpha_{12} + c.c.) + \Gamma_{21}\rho_{22} \quad (1a)$$

$$\rho_{22}' = (\tfrac{1}{2} i\Omega_1 \alpha_{12} + c.c.) + (\tfrac{1}{2} i\Omega_2 \alpha_{32} + c.c.) - \gamma_2 \rho_{22} \quad (1b)$$

$$\rho_{33}' = -(\tfrac{1}{2} i\Omega_2 \alpha_{32} + c.c.) + \Gamma_{23}\rho_{22} \quad (1c)$$

$$\alpha_{12}' = \tfrac{1}{2} i\Omega_1 {}^*(\rho_{22} - \rho_{11}) - \tfrac{1}{2} i\Omega_2 {}^* \alpha_{13} - (\tfrac{1}{2}\gamma_2 + i\delta_1)\alpha_{12} \quad (1d)$$

$$\alpha_{32}' = \tfrac{1}{2} i\Omega_2 {}^*(\rho_{22} - \rho_{33}) - \tfrac{1}{2} i\Omega_1 {}^* \alpha_{13} {}^* - (\tfrac{1}{2}\gamma_2 + i\delta_2)\alpha_{32} \quad (1e)$$

$$\alpha_{13}' = \tfrac{1}{2} i\Omega_1 {}^* \alpha_{32} {}^* - \tfrac{1}{2} i\Omega_2 \alpha_{12} - i(\delta_1 - \delta_2)\alpha_{13} \quad (1f)$$

Where, $\delta_1 = \omega_1 - (\varepsilon_2 - \varepsilon_1)/h$, $\delta_2 = \omega_2 - (\varepsilon_2 - \varepsilon_3)/h$: frequency detuning of two lasers.

$\varepsilon_1, \varepsilon_2, \varepsilon_3$, h: three unperturbed energy levels and Planck constant.

$\Omega_1 = (\boldsymbol{\mu}_{21} \cdot \mathbf{E}_1)/h$, $\Omega_2 = (\boldsymbol{\mu}_{23} \cdot \mathbf{E}_2)/h$: Rabi frequencies according with |1>, |3> to |2> transitions respectively.

$\alpha_{12} = \rho_{12}\exp(-i\omega_1 t)$, $\alpha_{32} = \rho_{32}\exp(-i\omega_2 t)$, $\alpha_{13} = \rho_{13}\exp(-i(\omega_1 - \omega_2)t)$: the rotating-wave density-matrix elements.

Γ_{21}, Γ_{23} : decay rates for transition |2>-|1> and |2>-|3>.

γ_2 : total state |2> decay rate.

Assuming above three atomic states consist of a close system, so $\Gamma_{21} + \Gamma_{23} = \gamma_2$.

υ : atomic velocity in the beam.

$\tau = l/\upsilon$, $T = L/\upsilon$, l and L are the transit times and lengths of interaction zones and drift region.

In (1), the rotating-wave approximation, electric-dipole approximation are employed, and the electric field vector exciting the atomic transition is determined by the following form,

$$\mathbf{E}(\mathbf{r}, t) = \frac{1}{2}(\mathbf{E_1}(\mathbf{r})\exp(-i\omega_1 t) + c.c.) + \frac{1}{2}(\mathbf{E_2}(\mathbf{r})\exp(-i\omega_2 t) + c.c.) \quad (2)$$

In order to calculate numerically, we assume that the temperature of the Cesium beam is 100°C, l=2.6mm, L= 0.26m, $\Omega_1 = \Omega_2$, and atoms enter zone A at t=0. The laser linewidth is not taken into account. Before entering zone A, all atoms are pumped to level state |3>, thus in zone A, the initial conditions for solving the equations (1) are as follows: $\rho_{11}(0) = 0$, $\rho_{22}(0) = 0$ $\rho_{33}(0) = 1$, $\alpha_{12}(0) = 0$, $\alpha_{32}(0) = 0$, $\alpha_{13}(0) = 0$. For the drift region and zone B, the initial conditions are obtained from the solutions of the previous interaction region.

We also assume that ω_1 has been fixed at the |1>-|2> transition frequency, and ω_2 is scanned through the |3>-|2> transition frequency. In the zone B, $\alpha_{13}(\tau_A + T + \tau_B)$, related to the ac Stark effect, is calculated under the optimal intensity of two lasers [6]. The final result should be an average over the atomic velocity distribution:

$$\langle \alpha_{13}(\tau_A + T + \tau_B) \rangle_{average} = \int_0^\infty \alpha_{13}(\tau_A + T + \tau_B) \cdot \rho(\upsilon) d\upsilon \quad (3)$$

Here $\rho(\upsilon)$ is the Maxwellian beam velocity distribution. The final result of (3) is showed in Fig.2 at different frequency-detuning scales. The calculation is limited to monochromatic, otherwise one has to integrate over the linewidth of two laser with a laser intensity expression as a function of frequency. Our calculation follows the procedure as: Step 1, setting initial condition; Step 2, Using the set initial condition to calculate the zone A interaction; Step 3, Using the results from Step 2 as new initial condition to calculate the dark zone interaction; Step 4, Using the results from Step 3 as another new initial condition to calculate the zone B interaction.

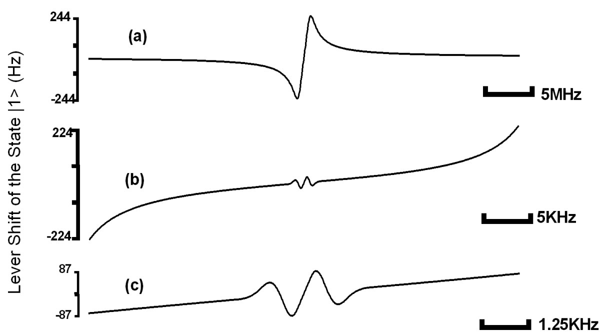


Fig.2 The ac Stark level shift in Ramsey-Raman configuration as a function of detuning frequency of Raman transition at different frequency scales.

III. Discussion

The calculated results of ac Stark shifts in Raman-Ramsey configuration are showed in Fig.2. An interesting new feature appears at the central region within 2kHz region, and it is an interference of two-photon ac Stark effects in two-zone Raman-Ramsey interactions. This interference is physically caused by the phase shift due to the interference between two ac Stark effects taking place between two Raman-Ramsey zones, thus is a function of free drift time T in the dark zone L. Although the ac Stark shift in a two-zone Raman interaction has been calculated theoretically and measured experimentally [6], this interference effect reported here is a new phenomenon. It is worth noting that it is not so easy to measure this new phenomenon experimentally, the technical requirement for measuring it is similar to what is summarized in [1-3]. Experimentally, the measured ac Stark shift in [6] should be a Raman-Ramsey ac Stark effect, the interference phenomenon has not been observed in [6] is due to the special requirement on measurement.

As an example, a 0.89 $\mu W / cm^{2}$ P laser intensity at a detuning of 300Hz in a Cs-beam Raman clock in the configuration with above parameters would cause a frequency shift of 10^{-2} Hz to state |1>, according to the above calculation. The interference effect reported here also can be observed in the new Ramsey-CPT configurations [13-15].

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