Sensitive measurement of phase shifts due to the ac Stark effect in a Ca optical Ramsey interferometer

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We constructed an optical Ramsey atomic interferometer, which has a resolution of 8 fm for the difference between arms of the interferometer, and used it to examine the phase shift due to the ac Stark effect of the excited state of the intercombination line ($^1S_0$-$^3P_1$) of Ca. It was clearly observed that the phase shift is in proportion to the field power and in inverse proportion to the detuning frequency of the laser. The proportionality coefficient obtained was in good agreement with the theoretical one.

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INTRODUCTION

Atomic interferometry is expected to be one of the most powerful tools for high-precision measurement [1]. Since it was pointed out that the interaction geometry of optical Ramsey resonance with four traveling-wave laser fields forms an excellent atomic interferometer [2], two distinct results showing interferences of atomic waves have been presented. In optical Ramsey-fringe spectroscopy, the phase shifts between the atomic partial waves have been measured precisely from the frequency shift of the Ramsey resonance. First, the Sagnac effect obtained by means of rotating the interferometer was measured successfully by Riehle *et al.* using the Ca matter wave in a rotating beam [3]. Next, phase shifts of the exciting laser fields, the so-called "ac Stark effect" were measured by two groups, Riehle *et al.* [4] and Sterr *et al.* [5], using a Ca Ramsey interferometer and a Mg Ramsey interferometer, respectively.

The measurement of a phase shift due to the ac Stark effect [6] is an example of the state-selective use of atomic interferometry, because one partial wave of the interferometer, which is labeled according to the internal state, is decelerated or accelerated by dipole forces in the inhomogeneous intensity profile. The dipole force has been explained well by a dressed-atom approach to atomic motion in laser light [7]. The two experiments above show qualitatively that the phase shifts are directly proportional to the power of the extra laser beam and inversely proportional to the detuning frequency of the extra laser beam, as expected from the theory. However, quantitative discussions were not given in those papers. In both experiments, atoms in the ground state were affected by the ac Stark effect. On the other hand, the phase shift of the excited state caused by the ac Stark effect has not yet been measured, but is also possible if we use an extra laser whose frequency is tuned close to the allowed transition frequency between the excited state and an upper state. In such a case, we will observe the dependence of the phase shift with the opposite sign, since the other arm in the interferometer, unlike the case of the ground state, is affected by the ac Stark effect.

The authors have developed a measurement system of frequency differences between two independent Ramsey resonances of the Ca intercombination line in order to evaluate the stability and accuracy of a frequency-stabilized dye laser by means of Ramsey resonance as a new wavelength standard [8]. The present system shows that the resolution of measurement is 70 Hz for integration time of 100 s, which corresponds to 1.4×10^{-13} of resonance frequency [9]. The de Broglie wavelength λ_d is 12 pm for calcium moving at a thermal velocity of $v=800$ m/s. Therefore, it will be possible to reduce remarkably the experimental uncertainty of the phase shift of atomic partial waves to an accuracy of 4 mrad under our condition of $2D=7$ mm. It should be noted that the detectable path difference between two arms of the interferometer corresponds to only 8 fm.

In this paper, we describe the precise measurement of phase shifts due to the ac Stark effect of the excited state of the Ca intercombination line using a frequency-stabilized Ca Ramsey interferometer. The authors also present an explicit relationship based on the dressed-atom approach for the phase shift due to the ac Stark effect, and compare it with the experimental results.

PRINCIPLE

A diagram of the Ca Ramsey interferometer under an ac Stark field is shown in Fig. 1, together with a partial level scheme of the Ca atom. The diagram represents the high-frequency component of the recoil doublet [2]. Atoms interact and exchange momentum sequentially with four-traveling waves, which are two counterpropagating pairs of equally spaced traveling waves ($\lambda=657$ nm).

The two trajectories of atoms in space, which form a closed loop, are responsible for the Ramsey fringe [10,11]

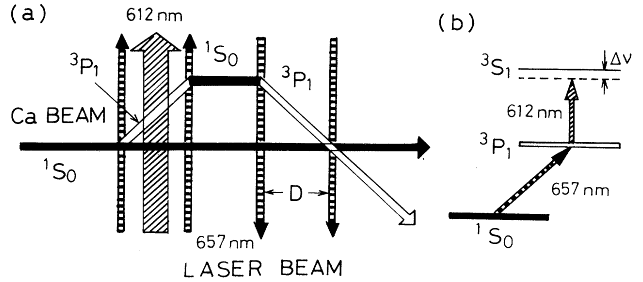

FIG. 1. (a) Diagrammatic representation of optical Ramsey interferometer under ac Stark field. (b) Energy diagram for relevant transitions of Ca.

and also compose an atomic interferometer [2,12]. The resonance condition of the Ramsey fringes is described by

$$2\pi(\delta\nu\pm\delta)(2D/v)+\Delta\psi+\Delta\phi=0\ , \tag{1}$$

where $\delta\nu$ is the shift frequency of the Ramsey resonance, δ is the recoil shift, $\Delta\psi$ is the phase shift of matter wave, $\Delta\phi$ is the phase difference of the laser beam, and D is the separation of laser beams. In the free zone between the first and second Ramsey excitations (or the free zone between the third and the fourth), atoms in one arm are in the excited state and atoms in the other arm are in the ground state. Therefore we can retard the matter wave in one arm state selectively by applying an additional laser beam which is resonant with the selected states. The same retardation is also applied to the Ramsey interferometer at the low-frequency recoil component at the same time.

Riehle *et al.* and Sterr *et al.* interpreted the phase shift due to the ac Stark effect as being proportional to the laser power inversely proportional to the detuning frequency of the laser [4,5]. Here we expand their interpretations to the Gaussian laser beam and introduce the proportional coefficient α for the phase shift. The ac Stark effect is described well by the dressed-atom approach [7]. For blue detuning of the laser frequency, atoms in the resonant level moving through the laser beam with electric field of $E(x)$ are decelerated towards the center of the beam and then accelerated again to the former velocity through change in the potential energy $U(x)$ of the dressed state. From Eq. (3.20) in Ref. [7], $U(x)$ is

$$U(x)=h\Omega^2/(8\pi\Delta\nu)\ , \tag{2}$$

where Ω is Rabi angular frequency and equals $|\mu E(x)/\hbar|$ (μ is the dipole moment). $\Delta\nu$ is the detuning frequency from the resonance frequency. Therefore, this part of the wave packet is reversed in comparison with that in the other arm of the interferometer, where atoms are in a nonresonant state. On the other hand, for red detuning, the atoms are accelerated and decelerated so that the wave packet advances. The corresponding phase shift $\Delta\psi$ is given under the assumption that $U(x)$ is small compared with the atomic kinetic energy,

$$\Delta\psi=-\int U(x)dx/(\hbar v)\ . \tag{3}$$

Therefore, the frequency shift of the Ramsey resonance from the resonance frequency is

$$\delta\nu=\int U(x)dx/(2hD)\ . \tag{4}$$

The electric amplitude $E(x)$ of the Gaussian beam with power P is given by

$$E(x)=[2P/(\epsilon_0 c\pi w^2)]^{1/2}\exp[-(x/w)^2/2]\ , \tag{5}$$

where w is the beam waist. When atoms pass through the center of the laser beam, the frequency shift of Ramsey resonance is given by

$$\delta\nu=[\mu^2/(4h^2\epsilon_0 c\pi^{1/2}Dw)](P/\Delta\nu)\ . \tag{6}$$

Since $\mu^2=\epsilon_0 h\lambda^3/(16\pi^3\tau)$, ultimately, the frequency shift of the Ramsey resonance is

$$\delta\nu\equiv\alpha(P/\Delta\nu)=[\lambda^3/(64hc\pi^{7/2}Dw\tau)](P/\Delta\nu)\ . \tag{7}$$

Therefore, the frequency shift depends linearly on the power and inversely on the detuning frequency of the laser. The proportional coefficient α is 1.43×10^{21} $[\lambda^3/(Dw\tau)]\ \mathrm{J^{-1}\,s^{-1}}$.

EXPERIMENT

Our experimental setup is shown in Fig. 2. The high-resolution dye laser spectrometer used for the Ramsey excitation was described precisely in another paper [13]. The output beam from the prestabilized dye laser, which emits λ of 657 nm, was split into two beams, each of which was shifted in frequency by means of an acousto-optic modulator driven by a voltage-controlled oscillator and guided to one of the two Ramsey apparatus. In each Ramsey apparatus, a thermal calcium atomic beam with the most probable velocity of 800 m/s was generated from an oven at a temperature of 700 °C. The Ca atom was excited to the $^3P_1$ state by Ramsey excitation ($\lambda=657$ nm) [8,14]. The separation D between neighboring beams propagating in the same direction was 3.5 mm

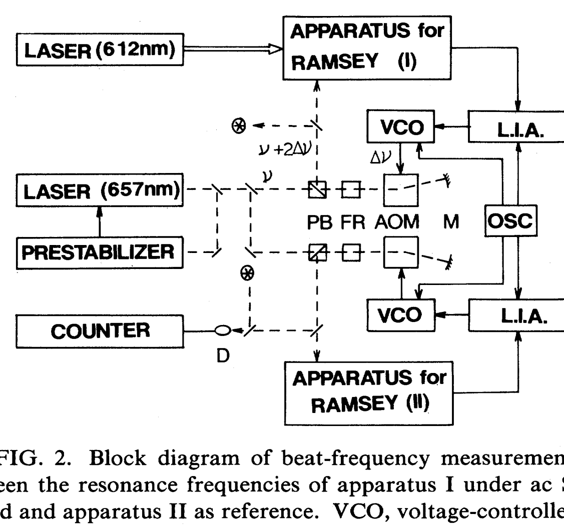

FIG. 2. Block diagram of beat-frequency measurement between the resonance frequencies of apparatus I under ac Stark field and apparatus II as reference. VCO, voltage-controlled oscillator; L.I.A., lock-in amplifier; OSC, oscillator; PB, polarization beam splitter; FR, Faraday rotator; AOM, acousto-optic modulator; *M*, mirror; *D*, detector.

and the excitation power of laser beams was about 2 mW. Under these conditions, the fringe width was about 60 kHz, so that two components of the recoil doublet overlapped and one single pattern of the Ramsey fringes was observed.

The additional ac Stark field was applied to one of the two Ramsey apparatus, as shown in Fig. 1. A laser beam whose frequency was tuned close to the transition frequency between the $^3P_1$-$^3S_1$ states ($\lambda = 612$ nm) was introduced into the dark zone between the first and second Ramsey excitation beams. It acts on atoms which are in the excited state in one arm of the interferometer. The beam waist of the laser beam was 0.5 mm, and intensities and detuning frequencies from the resonance were varied. Usually, σ polarization was used for excitation from $m=0$ to ± 1. The resonance linewidth is several hundred megahertz at a pump power of several milliwatts [15].

The Ramsey fringe pattern was observed by monitoring the fluorescence from $^3P_1$. In order to determine the center of the Ramsey fringe, the first-derivative signal of the fluorescence curve generated by frequency modulation with a small modulation width of 20 kHz was used, so that the effect of the background (for example, saturated absorption signal) could be removed. The first-derivative signal was also used as a discriminative signal for the stabilization of the laser frequency to the Ramsey resonance. The discriminative signal from the Ramsey resonance was fed to the voltage-controlled oscillator so that the output frequency was tuned to the center of the central Ramsey fringe by the acousto-optic modulator.

The other Ramsey apparatus with no additional laser beam was used as a frequency reference. Then the phase shift due to the ac Stark effect in the first Ramsey apparatus was observed as a shift of frequency from the reference frequency by means of the beat-frequency measurement of the two laser beams stabilized to the two Ramsey resonances. In advance, the accuracy of this system was evaluated by measuring the Allan variance of the beat frequency between the two stabilized lasers. The Allan variance at an integration time of 100 s was 70 Hz, which corresponds to 1.4×10^{-13} of the transition frequency [9].

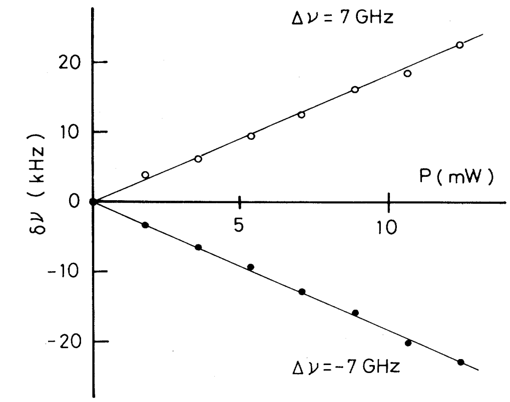

FIG. 4. Measured frequency shift of Ramsey resonance vs laser power. ○, detuning frequency of 7 GHz; ●, detuning frequency of −7 GHz.

RESULTS AND DISCUSSION

Typical Ramsey fringe patterns demonstrating the light-induced shift are shown in Fig. 3. The 612-nm laser with an output power of 12.5 mW was introduced. For negative detuning of 3.6 GHz, the fringe center shifts to the low-frequency side, as shown in Fig. 3(a), although the saturation dip remains unaffected in both frequency and signal size. When the frequency of the laser coincides with the exact resonance, the fringe pattern disappears and only the saturated absorption dip is seen [Fig. 3(b)] with a smaller signal size, since the process of Ramsey resonance is destroyed [16,17]. For positive detuning of 3.6 GHz, the center of the Ramsey fringe shifts to the high-frequency side [Fig. 3(c)]. When the wavelength is changed by 2 nm from the resonance wavelength, the phase shift disappears and a normal Ramsey fringe pattern appears, as shown in Fig. 3(d). No other phase shift can be observed when the π polarization beam is applied,

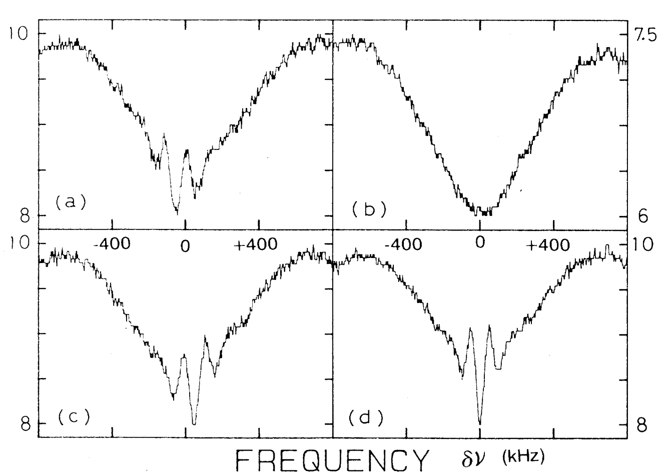

FIG. 3. Shift of Ramsey resonance due to the interaction of a laser tuned close to the $^3P_1$-$^3S_1$ transition of Ca for different detuning. (a) −3.6 GHz, (b) 0 GHz, (c) 3.6 GHz, (d) 2 nm.

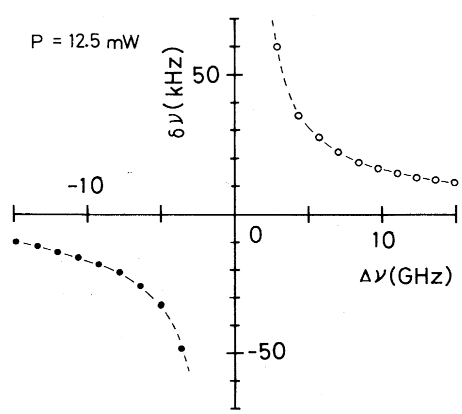

FIG. 5. Measured frequency shift of Ramsey resonance vs detuning frequency of laser. The power of the laser is 12.5 mW.

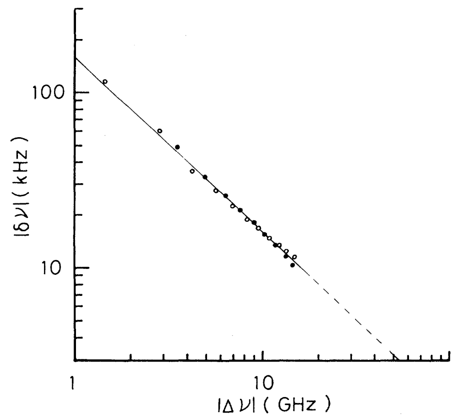

FIG. 6. Logarithmic expression of Fig. 5. The frequency shifts for positive (○) and negative (●) detunings are on a straight line with a slope of −1.

because the transitions of $\Delta J=0$ and $m'=0$ to $m''=0$ are not allowed.

Figure 4 shows the dependence of frequency shift on the laser power at a positive and a negative detuning of 7 GHz. The measured phase shift shows a linear frequency shift with an increment of laser power, with a positive slope for positive detuning and with a negative but same-sized slope for negative detuning. In the present experiment, we used a simple power meter to measure the laser power. Therefore, the slight discrepancy from the straight line may depend on an error in power measurement. This behavior is contrary to that of the phase shift observed with the light field resonanced to the ground state [4,5]. However, it is easy to understand that the different arm of the interferometer is affected by the ac Stark field in the present experiment.

Figure 5 shows the dependence of the frequency shift on the detuning frequency. It is seen that the frequency shift is in inverse proportion to the detuning frequency. In order to evaluate this relationship more precisely, the absolute value of frequency shift versus the absolute detuning frequency is plotted in a logarithmic graph, as shown in Fig. 6. The data are distributed in the vicinity of a straight line with a slope of −1. Therefore, the present results give better confirmation of the theory than the previous results, which are scattered around the theoretical curve. From the above results, it is confirmed that the dressed-atom approach [7] describes well the phase shift due to the ac Stark effect in the Ramsey interferometer.

In Table I, the measured phase shift is summarized with the previous results [4,5], together with the experimental conditions. In Eq. (7), the proportional coefficient α depends on several experimental parameters. Therefore, we deduced the coefficient α_d as $\alpha_d=\alpha(Dw\tau/\lambda^3)$ by substituting experimental data. The obtained value, 1.0×10^{21} $J^{-1}m^{-1}$, in the present experiment is slightly smaller than the theoretical value of 1.43×10^{21} $J^{-1}m^{-1}$. At the present experiment, the beam diameter of the applied ac field was almost the same as that of the Ramsey excitation beam. Therefore, the difference may be explained by the fact that atoms which move apart from the center of the laser beam are affected by the weaker power. Furthermore, it may also depend on the measurement errors of the laser power, beam waist, lifetime, and so on, since we did not measure them precisely. However, the agreement is somewhat better than the values obtained from the previous data, which are a few times bigger than the theoretical value.

TABLE I. Proportional coefficient of phase shift due to the ac Stark effect, together with experimental conditions, for three states.

Coefficient	Mg, $^1S_0$ Ref. [5]	Ca, $^1S_0$ Ref. [4]	Ca, $^3P_1$ Present work
λ (nm)	285	422	612
$\lvert\alpha\rvert$ ($J^{-1}s^{-1}$)	1.0×10^{16}	4.0×10^{15}	1.33×10^{16}
τ (ns)	2	4.5	10
D (mm)	4.5	8.5	3.5
w (mm)[a]	0.9	1.2	0.5
P (mW)	1	5	10
$\lvert\alpha_d\rvert$ ($J^{-1}m^{-1}$)	3.6×10^{21}	2.7×10^{21}	1.0×10^{21}

[a]w is defined in Eq. (5).

CONCLUSIONS

Using an optical Ramsey interferometer with high accuracy, we measured the phase shift due to the ac Stark effect of the excited state of the Ca intercombination line $^1S_0$-$^3P_1$. As expected, it was found that the sign of dependence of the phase shift is the opposite of that observed due to the ac Stark field of the ground state [4,5]. It was confirmed that the phase shift is a function of power and detuning frequency of the laser, in good accordance with the relationship given by the dressed-atom approach [7]. The proportional coefficient was almost the same as that estimated from the theory.

This method is also worthwhile as a nondestructive method for measuring the laser power or detuning frequency accurately [5]. Our interferometer has the potential to resolve the path difference of 8 fm between the two arms of an interferometer. Furthermore, the optical Ramsey interferometer can be used as a state-selective interferometer, which is one of the attractive features of the atom interferometer. Therefore, the optical Ramsey interferometer is expected to be a powerful sensor for tests of general relativity or quantum mechanics in the future.

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[1] M. Kasevich and S. Chu, Appl. Phys. B **54**, 321 (1992).
[2] Ch. J. Bordé, Phys. Lett. A **140**, 10 (1989).
[3] F. Riehle, Th. Kisters, A. Witte, and J. Helmcke, Phys. Rev. Lett. **67**, 177 (1991).
[4] F. Riehle, A. Witte, Th. Kisters, and J. Helmcke, Appl. Phys. B **54**, 333 (1992).
[5] U. Sterr, K. Sengstock, J. H. Muller, D. Bettermann, and W. Ertmer, Appl. Phys. B **54**, 341 (1992).
[6] A. M. Bonch-Bruevich and V. A. Khodovoi, Usp. Fiz. Nauk **93**, 71 (1967) [Sov. Phys. Usp. **10**, 637 (1968)].
[7] J. Dalibard and C. Cohen-Tannoudji, J. Opt. Soc. Am. B **2**, 1707 (1985).
[8] A. Morinaga, F. Riehle, J. Ishikawa, and J. Helmcke, Appl. Phys. B **48**, 165 (1989).
[9] A. Morinaga, N. Ito, J. Ishikawa, K. Sugiyama, and T. Kurosu, IEEE Trans. Instrum. Meas. (to be published).
[10] Ch. J. Bordé, Ch. Salamon, S. Avrillier, A. Van Lerberghe, Ch. Breant, D. Bassi, and G. Scoles, Phys. Rev. A **30**, 1836 (1984).
[11] A. Morinaga, Phys. Rev. A **45**, 8019 (1992).
[12] Ch. J. Bordé, in *Laser Spectroscopy,* edited by M. Ducloy *et al.* (World Scientific, Singapore, 1992), p. 239.
[13] A. Morinaga, N. Ito, and K. Sugiyama, Jpn. J. Appl. Phys. **29**, L1727 (1990).
[14] N. Ito, J. Ishikawa, and A. Morinaga, J. Opt. Soc. Am. B **8**, 1388 (1991).
[15] A. Morinaga, N. Ito, and T. Sakurai, Appl. Phys. B **54**, 29 (1992).
[16] F. Riehle, J. Ishikawa, and J. Helmcke, Phys. Rev. Lett. **61**, 2092 (1988).
[17] T. Kurosu and A. Morinaga, Phys. Rev. A **45**, 4799 (1992).