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Calcium-atom interferometer comprised of four copropagating traveling laser beams

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Four laser beams traveling in the same direction that split and reflect a thermal calcium atomic beam compose an atomic interferometer like the Mach-Zehnder optical interferometer. The interference performance of the atomic interferometer was examined by changing the phase of the induced dipole moment in the atomic wave due to the laser beams, or the phase of atomic "wavepacket" in an atomic trajectory due to the ac Stark effect. An interference signal with a visibility of more than 15% was obtained. This interferometer will be useful in the detection of weak signals that require a long integration time, since it is less sensitive to the fluctuation of the laser frequency compared with the optical Ramsey atomic interferometer.

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Atomic interferometers are expected to be used as sensitive accelerometers in a variety of precision measurements such as tests of relativistic effects or quantum mechanics [1]. Moreover, atomic interferometers have the potential for applications in new experiments where neutron or electron interferometry is not applicable, using the atom's internal energy structure. In recent years, several versions of the atomic interferometer have been presented [2–6]. Particularly, the optical Ramsey-Bordé atomic interferometer is used as a tool for precision measurements, because the phase shift of the atomic wave can be measured precisely by a frequency shift of the Ramsey fringe [7]. The Sagnac effect [2] and ac Stark effect [8–10] were measured using Ca or Mg atomic interferometers; however, the accuracy obtained is limited by the frequency stability of the laser at a long integration time.

On the other hand, four laser beams traveling in the same direction that split and reflect the atomic beam also make an atomic interferometer like the Mach-Zehnder interferometer. Such an atomic interferometer was discussed theoretically by Bordé [11] and Friedberg and Hartmann [12]. The interferometer is symmetric and therefore insensitive to atomic velocity. Furthermore, the interferometer is far less sensitive to frequency fluctuations of the laser than the optical Ramsey interferometer. Therefore, it is worthwhile causing the Mach-Zehnder interferometer to be realized for the purpose of detecting weak signals that require a long integration time.

In case of pulsed excitation, the Mach-Zehnder atomic interferometer with laser-cooled atoms and a series of three light pulses was devised by Kasevich and Chu [1,5]. They used the stimulated Raman transition, because metastable optical transitions that have large recoil velocities require an ultrastable laser to drive the transition. They observed the optical phase shift among three excitations in order to evaluate the gravitational acceleration, although it is not a phase shift occurring between two atomic wavepackets in free evolution. Therefore, it will also be interesting to observe the actual atomic phase shift between two trajectories as a demonstration of the capabilities of the atomic interferometer.

In this Rapid Communication, the authors present the realization of a Mach-Zehnder atomic interferometer comprised of a Ca thermal beam with a de Broglie wavelength of 12 pm and four copropagating laser beams, and the observation of the interference signal for phase shifts between two atomic waves in the interferometer.

Figure 1 shows a diagram of the Mach-Zehnder atomic interferometer. Owing to the energy and momentum exchanges during the resonant absorption and emission processes, the atomic waves coherently split into two components: i.e., the ground state and the excited state, with velocities differing due to the recoil effect in the direction of light propagation. At the first interaction of atom and light, a part of the atomic beam is excited to the upper state with recoil velocity in the direction of the light (the "upper" arm). At the second interaction, the atom in the upper arm emits light due to stimulation and reverts back to the original direction of motion. At the third interaction, atoms in the "lower" arm absorb photons and are excited. At the final interaction, atoms in the upper arm are excited again and both arms overlap if the spacing between the first and second interactions is equal to that between the third and fourth. This configuration forms a closed loop and results in an interference of the wavepackets at the final zone. For simplicity, other possible trajectories of atoms are omitted in the figure, although two of them make the other interferometer.

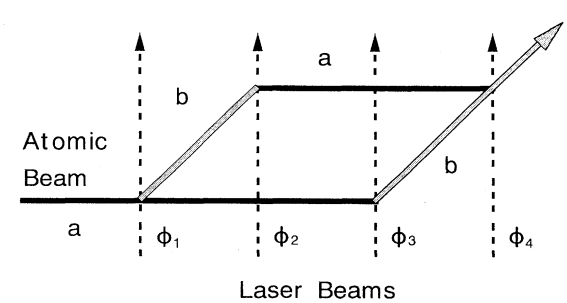

FIG. 1. Mach-Zehnder atomic interferometer with four copropagating laser beams. a, ground state; b, excited state; and ϕ_i, phase of the ith laser beam at time t.

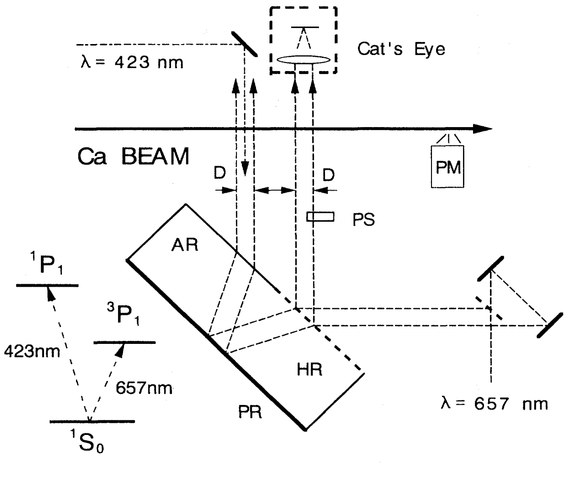

FIG. 2. Experimental setup for the Mach-Zehnder atomic interferometer, together with a partial energy diagram of Ca. The cat's eye is used for beam alignment. A laser beam with a wavelength of 423 nm is used to shift the atomic phase due to the ac Stark effect. PS, phase shifter; PM, photomultiplier; AR, antireflection; HR, half reflection; PR, perfect reflection.

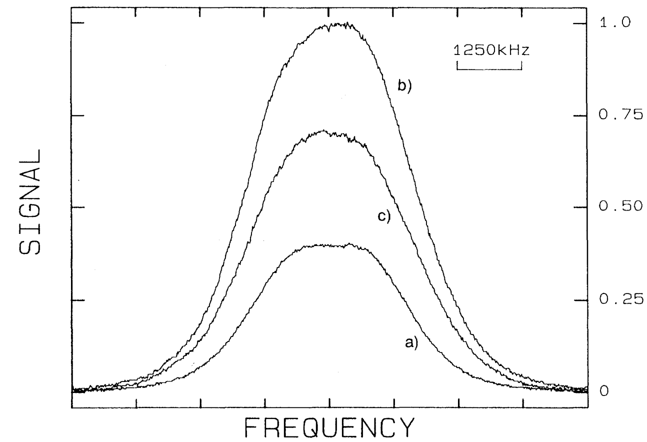

FIG. 3. Fluorescence spectra from the $^3P_1$ state of Ca. (*a*) excitation by single laser beam; (*b*) and (*c*) maximum and minimum spectra excited by four copropagating laser beams with proper optical phase shift, respectively.

The phase factor of this interferometer can be calculated by considering the phase factor arising from the atom's interaction with light and that arising during the atom's free evolution between interactions. Due to the symmetry of the geometry, the total phase shift between two arms is canceled, except for the following two phase shifts. One is the optical phase difference of four traveling waves and is given by

$$\Delta\phi = -\phi_1 + \phi_2 + \phi_3 - \phi_4,$$

where ϕ_i is the optical phase of the ith laser beam at time t. The other is the atomic phase difference between both trajectories arising due to a perturbation, $\Delta\varphi$. As a result, the total phase shift is $\Delta\psi = \Delta\phi + \Delta\varphi$. Thus, the interference is not affected by the detuning frequency of the laser, unlike the optical Ramsey interferometer [4]. Around $\Delta\varphi = 0$ it is also less sensitive to change of de Broglie wavelength, i.e., the atomic velocity, like a white-fringe interferometer. In addition, the phase shift is not affected by the transverse velocity of atoms due to atomic beam collimation, unlike the two-zone Ramsey resonance. Of course, it is not affected by the detector position, unlike Young's conventional slit interferometer.

The experimental setup for the Mach-Zehnder atomic interferometer is shown in Fig. 2. The four laser beams copropagating in the same direction are realized by using an optical parallel plate that is made of fused silica. The plate is 80 mm in diameter and 25 mm in thickness. The surface roughness is λ/20 for the wavelength used, and both surfaces are parallel to each other within 0.5 s. One-half of the front surface of the plate reflects 50% of the beam, whose incidence angle is 45°, and polarization is S wave. The other half is coated with an antireflection coating. The rear surface has a perfect reflection coating. The plate is carefully placed in the mirror mount and set such that the reflected beams cross the atomic beam perpendicularly. Therefore, this plate produces two parallel beams within 1 s with about the same power. The spacing between the two parallel reflected beams is 2 cm. The incident laser beam is split into two beams by a beam splitter placed in front of the optical plate. The two beams are aligned with the two parallel beams with a space of 5 mm by means of a cat's eye retroreflector, which is set to the laser beams for alignment. As a result, the four laser beams propagate parallel and in the same direction, and the beam spacing between the first and second laser beams is equal to that between the third and fourth.

A thermal calcium atomic beam, the most probable velocity of which was 800 m/s, was generated from an oven at a temperature of 700 °C. The Ca beam was collimated to give a residual Doppler full width at half maximum of about 3 MHz. The high-resolution dye laser spectrometer prestabilized to hyperfine components of iodine molecules [13] was used for the excitation to the $^3P_1$ state from the Ca atom ground state of $^1S_0$. The wavelength of the output laser was 657 nm and frequency fluctuation was about 20 kHz. The output frequency was scanned using an acousto-optic modulator. A small magnetic field was applied perpendicular to both the atomic beam and the laser beams in the interaction zone. The polarization of the laser beam was set so as to excite only the $\Delta m = 0$ transition. The population of the upper $^3P_1$ state was observed by monitoring the fluorescence from $^3P_1$ at about 300 mm downstream from the excitation region.

Using a cat's eye retroreflector set to the laser beams, two input beams to the optical parallel plate were precisely aligned so as to interfere with the reflected beams. With this alignment procedure, four parallel beams were obtained within 1 s. The power of each of the four laser beams was about 0.5 mW, and each beam interacted with the Ca beam at a right angle. A typical measured fluorescence spectrum is shown in Fig. 3. There were no clear differences in widths and profiles among the fluorescence spectra for each of the four beams.

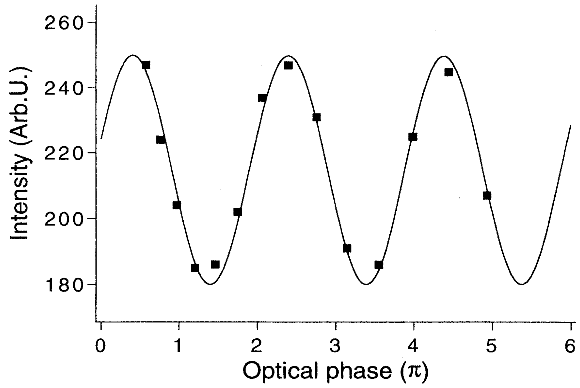

FIG. 4. Fluorescence signal versus optical phase shift. Data are fitted with a sinusoidal curve. The error of the data is equal to the point size.

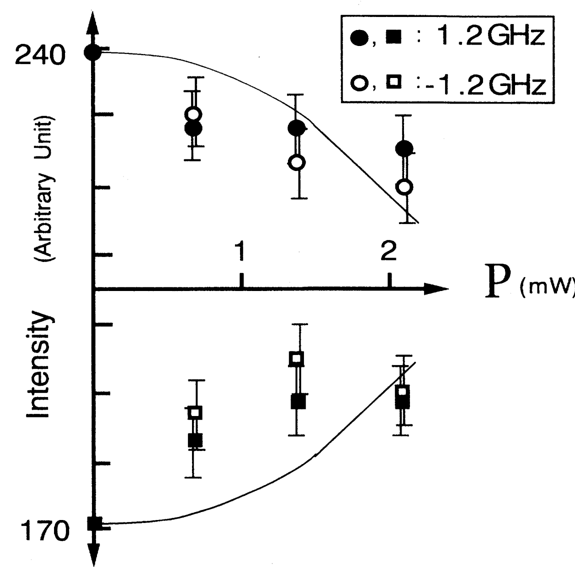

FIG. 5. Dependence of the fluorescence signal on the power of the ac Stark field and on the sign of the detuning frequency. A rough estimated cosine curve is given by solid lines.

First, the dependence of the population of the upper state on the optical phase shift was examined. The phase plate was inserted in the path of the fourth beam before interaction with the atomic beam. By changing the angle of the phase plate, the fluorescence from the upper state varied sinusoidally as a function of optical phase shift, as shown in Fig. 4. The variation is well described by a sinusoidal function of the optical phase shift, as expected. The spectra measured at the maximum and minimum fluorescence are shown in Fig. 3. The obtained visibility is about 16%. The visibility depends on the amplitudes of the laser beams. The estimated maximum visibility is 50%, when the amplitude of each laser beam is such that it results in a $\pi/2$ pulse. However, we observe the velocity averaged visibility due to integration over a large velocity distribution in the thermal atomic beam [14].

This result confirms that the closed geometry makes the atom interferometer. On the other hand, the fluorescence signal does not depend on the phase shift between two beams when we excite atoms with only two laser beams. In this case, the atomic trajectories do not form closed configurations.

Next, the dependence of the population of the upper state on the atomic phase shift was demonstrated. The atomic phase was changed by using the ac Stark effect of the ground state, and it shifted linearly on the power of the ac Stark field [8]. In the free zone between the first and second interactions, a blue laser of $\lambda = 423$ nm was introduced as the Stark field (Fig. 2). The frequency was detuned by about 1.2 GHz from the resonance, i.e., out of the resonance frequency. The laser power and sign of detuning frequency were changed. Before the blue laser was introduced, the fluorescence signal from the $^3P_1$ state was maximized or minimized by adjusting the phase shifter. The results are summarized in Fig. 5. The coincidence of the expected cosine curves and results is not good because of a large-amplitude fluctuation of 423 nm. However, it is seen that the fluorescence signal decreases from maximum (circles) or increases from minimum (squares) with increasing laser beam power, in spite of the sign of detuning frequency. This result shows that the variation of fluorescence arises from the phase difference between the atomic waves of the two arms in the first zone. We could not observe a phase shift of more than $\pi/2$, because we did not have sufficient ac field power.

In the case of the optical Ramsey atomic interferometer, we can measure the phase shift accurately based on the detuning frequency of the Ramsey fringe. However, it also should be noted that the obtained phase shift fluctuates due to the fluctuation of laser frequency. If the signal intensity is very small, integration time becomes long in order to obtain a better signal-to-noise ratio. This demands an ultrastable laser for the optical Ramsey interferometer. On the other hand, the Mach-Zehnder atomic interferometer does not require such an ultrastable laser. Therefore, this interferometer will be useful for detection of a weak signal.

The Mach-Zehnder atomic interferometer comprising four cw copropagating laser beams was developed using a Ca thermal atomic beam. Interference signals for both the optical phase shift and atomic phase shift were observed. The difference between the Mach-Zehnder atomic interferometer and the optical Ramsey interferometer lies in the detuning sensitivity of the laser frequency. Using the Mach-Zehnder interferometer, the measurement of the polarizability of Ca [15] is now in progress and the Aharonov-Casher effect of the neutral atom [16] is in the planning stage. Even if the uniform dc electric field is applied to this interferometer, the dc Stark shift between both arms will be canceled out because of symmetry. Therefore, we can observe the Aharanov-Casher effect without the influence of the dc Stark effect.

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