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Coherent Population Trapping-Ramsey Interference in Cold Atoms *

CHEN Xi(陈曦)[1,2,3], YANG Guo-Qing(杨国卿)[1,2,3], WANG Jin(王谨)[1,2**], ZHAN Ming-Sheng(詹明生)[1,2]
[1]*State Key Laboratory of Magnetic Resonance and Atomic and Molecular Physics, and Wuhan National Laboratory for Optoelectronics, Wuhan Institute of Physics and Mathematics, Chinese Academy of Sciences, Wuhan 430071*
[2]*Center for Cold Atom Physics, Chinese Academy of Sciences, Wuhan 430071*
[3]*Graduate University Chinese Academy of Sciences, Beijing 100049*

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We demonstrate an experimental observation of coherent population trapping-Ramsey interference in cold ^{87}Rb atoms by employing the time-domain separated oscillatory fields' method. The interference fringe with line width of 80 Hz is obtained. We propose a novel method to measure the cold atom number. The measurement is insensitive to the pump beam intensity, the single photon detuning and even the initial state population. We use this method to normalize the interference signal and to improve the signal-to-noise ratio significantly.

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Coherent population trapping (CPT) is a phenomenon that occurs when two laser fields interact with a three-level atomic system. When the detuning of the laser frequencies satisfies the two-photon resonance condition, atoms will be coherently trapped in the dark state, and will stop absorbing laser fields. This phenomenon has been investigated by many groups,[1−6] and has numerous applications. One can use counter-propagating coherent beams to drive zero-velocity atoms into the dark state and cool atoms below the single-photon recoil energy.[7] One can also use CPT to measure the ground state Zeeman splitting and realize a sensitive magnetometer.[8,9] CPT signal reflects the energy level information of the ground state, and the 0-0 transition of ^{87}Rb atoms is insensitive to the magnetic field in the first order, so we can use the CPT signal to implement an atomic frequency standard. In recent years, the vapor cell CPT atomic clocks have become a new type of commercial atomic clock.[1−4] Unlike the traditional microwave-optical double resonance atomic clock, a passive CPT atomic clock has an all-optical configuration. It neither needs the microwave cavity nor the spectrum lamp, therefore having small size and low power cost.[2,10] To build a vapor cell CPT atomic clock, researchers usually use microwave filed to modulate the current of a vertical-cavity surface-emitting laser (VCSEL) and to create sidebands as the coherent beams. The disadvantage of this method is that the two sidebands cannot be separated, and they will pump atoms into a dipole forbidden trap state, this will decrease the contrast of the CPT signal.[1] To overcome this problem, several schemes have been proposed, for example, the push-pull scheme,[11] the orthogonal circular polarization with counter-propagating waves,[12] and the orthogonal linear polarization CPT beam.[13]

However, due to the thermal atomic motion and collision between alkali metal atoms and the background gases, the line width of CPT peak in hot atoms is broaden and the central frequency of the CPT signal is shifted. This leads to decreasing the frequency stability and accuracy of the atomic clock. Using laser cooling and magnetic-optical trapping (MOT), one can easily cool atoms below 1 mK, then the above temperature related effects will be greatly depressed.[14,15] More importantly, the coherent time of the CPT state is much longer in cold atoms than in the hot gas. As we know, coherent pulses can be used to produce CPT-Ramsey fringes,[13] and the fringe width depends only on the transit time T as $1/2T$. Thus long coherent time means that we can increase the transit time, and obtain a very narrow CPT-Ramsey fringe width which could not be achieved in hot atoms. In this work, we use the lin ⊥ lin CPT beams to prepare CPT state in cold ^{87}Rb atoms, and use the time-domain separated oscillatory fields' method to obtain narrow CPT-Ramsey fringe.

We use a relatively long coherent pulse to completely pump the cold atoms to the CPT state. After waiting for a transit time T, we turn on a much shorter coherent pulse again. This pulse interferes with the first pulse through the atoms in the CPT state. Thus if we scan the frequencies detuning of the coherent beams, we can obtain a CPT-Ramsey fringe with a width of $1/2T$. The first pulse, defined as preparation pulse, pumps atoms into the dark state. The second pulse, named as detection pulse, interfering with the first pulse and inducing the fluorescence. Unlike the

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**Corresponding author. Email: wangjin@wipm.ac.cn

traditional $\pi/2$–$\pi/2$ pulse sequence, the preparation pulse is more like a π-pulse, and the detection pulse is much shorter. This is because if the detection pulse is long enough, it will pump the atoms into the dark state again, and will eliminate the interference of the two pulses.

The experimental setup is shown in Fig. 1, it includes a MOT, coherent beams, fluorescence collection system, time sequence control and data acquisition system.

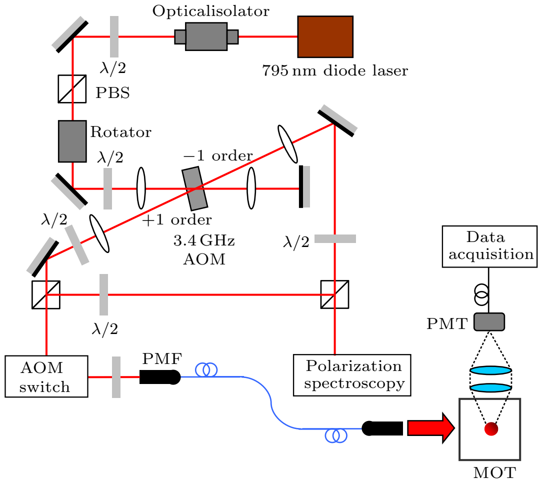

Fig. 1. Experimental setup. MOT: magneto-optical trap; PMT: photo multiplier tube; PMF: polarization-maintaining fiber; AOM: acousto-optical modulator; PBS: polarization beam splitter.

One advantage of the CPT atomic clock is the small clock size. To maintain this advantage in cold atom device, we built a single-beam mini MOT to minimize the experimental system.[16] Two sets of homemade 780 nm external-cavity diode lasers were used as the cooling and repumping lasers. The frequencies of trapping lasers were stabilized using polarization spectroscopy. A 110-MHz acousto-optical modulator (AOM) was used to shift the frequency and to switch the trap beams. Then we coupled the laser beams to a single-mode polarization-maintaining fiber (PMF) and sent them to the mini MOT. About 10^7 ^{87}Rb atoms were successfully cooled and trapped in the mini MOT.

The CPT lasers were generated by an external-cavity diode laser and an AOM. The 795 nm laser beam double-passed the 3.4 GHz AOM to create ±1 order beams, and the 3.4 GHz AOM was driven by a signal generator. We locked the frequency of -1 order beam to the peak of the $F=2\rightarrow F'=1$ transition, and then combined the two diffraction beams with a polarization beam splitter (PBS) to form the lin $\perp$ lin coherent beams. We used two 80 MHz AOMs to switch the coherent beams without change their frequencies. The $1/e$ diameter of output beams was 4 mm and all of the cold atoms in the mini MOT were included in the beams. Three pairs of Helmholtz coils were used to eliminate the stray magnetic field, only leaving a 300 mG uniform magnetic field along the coherent beams as the quantization axis.

An optical collection system with a designed solid angle 0.28 was used to collect the fluorescence. The fluorescence was detected by a photo multiplier tube (PMT). A multifunction data acquisition card was used to record the signal and to control the AOM drivers, signal generator and the quadrupole magnetic field.

The CPT state is very fragile, so we have to shut off the MOT to prepare the CPT state. We turned on the MOT and the coherent beams alternately with a 1 s duty cycle, 990 ms for the MOT, and 10 ms for the coherent beams. After turning off the MOT, we waited for 0.5 ms to let the quadrupole magnetic field attenuated to zero, and turned the coherent beams on for 2 ms to completely pump atoms into the ground CPT state $F=2$, $m_F=0$ and the $F=1$, $m_F=0$. After a few ms, we turned on the coherent beams again for 100 µs. Then we detuned the laser frequency and recorded the fluorescence induced by these two pulses in each cycle.

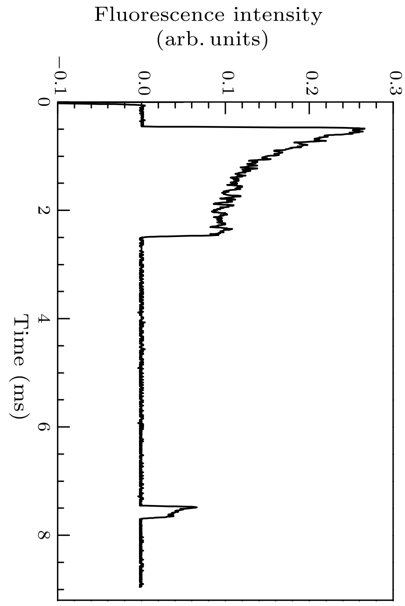

Fig. 2. Fluorescence signal of the cold ^{87}Rb atoms induced by the preparation and detection CPT pulses.

A typical fluorescence signal is shown in Fig. 2. The two steps are fluorescence induced by the preparation and detection pulse. We can see that fluorescence of the first pulse turns to zero because the atoms are pumped to the CPT state. The CPT-Ramsey fringe signal is shown in Fig. 3. This fringe is normalized by the cold atom number, and we will discuss it later. The fringe's line width is about 80 Hz. It is much narrower than the traditional CPT line width in hot vapor which is in the order of kHz,[1] and it can also be narrower than the hot vapor CPT-Ramsey line width which is mainly limited by the coherent time.[13]

Due to the fluctuation of cold atom number, the signal to noise ratio (SNR) of the Ramsay fringe is poor. The maximum fluctuation is about 10%. We need to normalize the detection fluorescence signal and to eliminate the noise caused by the atom number fluctuation.

Usually, atom number was measured by a resonant probe beam if the cross section and the intensity of the probe field are known. The cross section depends on laser detuning, polarization, line width and Zeeman shift, so it is difficult to determine the atom number accurately. To overcome this disadvantage, we can use the optical pumping process to determine the cold atom number.[17,18] This method does not depend on the probe beam intensity, detuning, polarization and etc. CPT is a kind of optical pumping process too, so we would like to calculate the fluorescence photon number emitted during the CPT pumping process and to find whether it can give the information of the atom number.

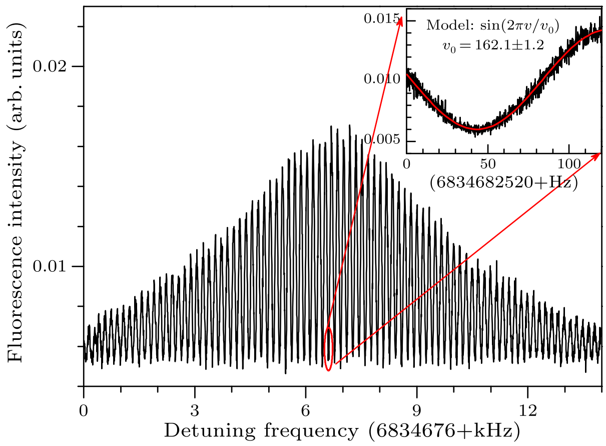

Fig. 3. Large range scan of the CPT-Ramsey fringe and detail range scan of the fringe, the total coherent beams intensity is 20 μW, and the transit time is $T = 6$ ms. A line width about 80 Hz is obtained.

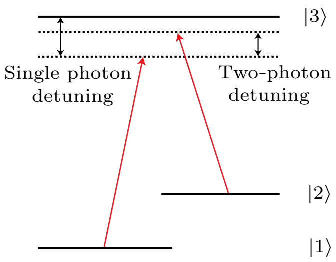

Fig. 4. Schematic diagram of an ideal Λ type three-level and two mode fields model.

As shown in Fig. 4, the fluorescence photon number induced by the CPT pumping process can be expressed as

$$N = \int_0^\infty n\Gamma\rho_{33}(t)dt, \tag{1}$$

where n is the cold atom number, Γ is the exited state decay rate, $\rho_{33}(t)$ is the density matrix element of the excited state $|3\rangle$. If the single photon detuning is zero and all the atoms are initially populated in the state $|1\rangle$, we can find an approximate analytical expression for $\rho_{33}(t)$ from the density matrix equation

$$\rho_{33}(t) = \frac{\Omega^2}{\Gamma^2}\exp^{-\frac{\Omega^2}{\Gamma}t}. \tag{2}$$

Substitute Eq. (2) into Eq. (1), then $N = n$. This means that the total photon number is exactly the same as the atom number. It depends neither on the Rabi frequency Ω of the pumping beams nor the excited state decay rate.

Define N/n as photon coefficient. When the single photon detuning is not zero or the initial state population is a superposition of the ground state $|1\rangle$ and $|2\rangle$, we numerically solve the density matrix equation to obtain $\rho_{33}(t)$, then substitute it to Eq. (1) to solve the coefficient. We find that the photon coefficient is still 1, it depends on neither the initial state population nor the single photon detuning when this detuning is in the range of the natural line width.

In our experiment, we simply divided the detection pulse fluorescence signal by the preparation pulse fluorescence signal in each cycle. By doing this we can suppress the noise caused by the atom number fluctuation. This method can significantly increase the SNR of the Ramsay signal. Figure 5(a) is a typical CPT-Ramsey fringe without normalization, and Fig. 5(b) is the same fringe after normalization. We can see that this effect is depressed.

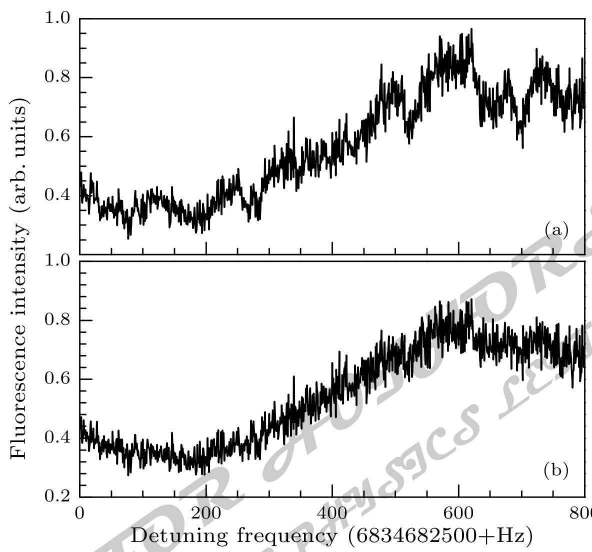

Fig. 5. CPT-Ramsay fringe before (a) and after (b) normalizing the cold atom number. The total coherent beams intensity is 20 μW, and the transit time is $T = 1$ ms.

The SNR of the CPT-Ramsey signal is still low even after normalizing the atom number. This is mainly because the length of detecting pulse is only 100 μs, which means that frequency noise of the coherent beams below 10 kHz cannot be averaged during the measurement.

In summary, CPT-Ramsey fringe line width as narrow as 80 Hz has been obtained in cold ^{87}Rb atoms, and a novel method to eliminate the signal noise caused by the cold atom number fluctuation is proposed and realized. This will helpful for improving the clock frequency stability of cold ^{87}Rb atomic clocks.

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