Enhanced laser cooling of rubidium atoms in two-frequency diffuse lights

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In this paper we describe an experiment of efficient cooling of \textsuperscript{87}Rb atoms in two-frequency diffuse laser lights. Compared with single frequency diffuse light, two-frequency diffuse lights have wider velocity capture range and thus can cool more atoms. In our experiment, the maximum number of cooled atoms can reach up to $3.9 \times 10^6$. Such a result is quite useful in building a compact cold atom clock.

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Cooling of atoms in diffuse laser lights is an all-optical laser cooling method with a wide velocity capture range compared with optical molasses. It was first applied in slowing and cooling of atomic beams \cite{1,2,3,4}. Later, three-dimensional cooling of Cs atoms from background vapor in one-frequency diffuse laser lights was also realized \cite{5,7}. This technique leads to a development of compact cold-atom clock (The HORACE) \cite{7,8,9}, which gives an appealing stability at $5 \times 10^{-13}$ at 1 sec. \cite{10}.

There are still some rooms for the improvement of the performance of the HORACE. For example, increasing the number of detected atoms can reduce both the quantum projection noise and the detection noise \cite{9}. This is especially useful for rubidium atoms because collision shift of cold rubidium atoms is much smaller than cesium \cite{11}. In this paper, we present an experiment of two-frequency diffuse light cooling of rubidium atoms directly from background vapor, with which more cold atoms are captured than in single-frequency diffuse light used in previous experiments \cite{5,7}.

As well known, the radiation force for a monochromatic laser on a two-level atom is

$$F = \hbar k \frac{\Gamma}{2} s \frac{s}{1 + s + (2\Delta/\Gamma)^2}$$

where, $\Gamma = 2\pi \cdot 6.066$MHz is the decay rate of the excited state, $s$ is the on-resonance saturation parameter, $\Delta$ is the detuning between laser and atom. In diffuse light, for an atom moving at velocity $\vec{v}$ and interacting with a laser beam with an angle $\theta$ with respect to $\vec{v}$, the detuning is $\Delta = \omega - \omega_a - k \cdot \vec{v} = \Delta + kv \cos \theta$, $\omega$ and $\omega_a$ are the frequency of laser and atomic transition respectively. We can easily have the force on a two-level atom in a pair of oppositely propagating light beams from Eq.\textsuperscript{1}, one with an angle $\theta$ with respect to the opposite direction of atomic velocity, and the other with an angle $\theta$ with respect to the same direction of atomic velocity:

$$F = -\hbar k \frac{\Gamma}{2} \frac{s \cos \theta}{1 + s + 4(\Delta + kv \cos \theta)^2/\Gamma^2}$$

$$+ \hbar k \frac{\Gamma}{2} \frac{s \cos \theta}{1 + s + 4(\Delta - kv \cos \theta)^2/\Gamma^2}$$

(2)

In diffuse light, the on-resonant light dominates the interaction process between the atom and the diffuse light. Thus Eq.\textsuperscript{2} is a good approximation for considering atomic motion in the diffuse light at the condition

$$\Delta + kv \cos \theta = 0$$

(3)

Obviously, for cooling, $\Delta$ must be negative. The lowest velocity for which the Eq.\textsuperscript{3} can be satisfied is $k v_{\min} = |\Delta|$ when $\theta = 0$. On the other hand, from Eq.\textsuperscript{2}, the radiation force drops as $\theta$ increases while the Eq.\textsuperscript{3} is still satisfied. For example, the radiation force drops to half of the maximum when $\cos \theta = 1/2$, which gives $k v_{\max} = 2|\Delta|$. Thus we have an efficient cooling range of velocity for a two-level atom in diffuse light $|\Delta| \leq kv \leq 2|\Delta|$. If we choose $\Delta = -\Gamma$, as typical optical molasses does, the capture velocity is $2\Gamma/k$, which is in the same order with typical optical molasses.

In order to increase the velocity capture range, the detuning $|\Delta|$ must be large, but large detuning leads to large final velocity of cooled atoms. A simple way to solve this problem is the use of multiple diffuse light frequencies as used by Ketterle \textit{et al.} in cooling of an atomic beam \cite{1}. Atoms with high velocity are cooled by large-detuned light, and those with low velocity by small-detuned light \cite{12}. In fact, the cooling of an atomic beam is more like the deceleration of atoms, while the cooling of atoms from background vapor is more like the accumulation of cold atoms besides cooling. Thus cooling from background vapor is more attractive because it has a simple structure and the cooled atoms is "localized" in a region where many experiments can be done. We calculated the force on a two-level atom in two-frequency diffuse lights as

$$F = -\hbar k \frac{\Gamma}{2} \sum_{n=1}^{2} \frac{s_n \cos \theta_n \alpha}{1 + 4(\Delta_n + kv \cos \theta_n)^2/\Gamma^2}$$

$$+ \hbar k \frac{\Gamma}{2} \sum_{n=1}^{2} \frac{s_n \cos \theta_n \beta}{1 + 4(\Delta_n - kv \cos \theta_n)^2/\Gamma^2}$$

(4)

where

$$\alpha = 1/[1 + \sum_{n=1}^{2} \frac{s_n}{1 + 4(\Delta_n + kv \cos \theta_n)^2/\Gamma^2}]$$

and

$$\beta = 1/[1 + \sum_{n=1}^{2} \frac{s_n}{1 + 4(\Delta_n - kv \cos \theta_n)^2/\Gamma^2}]$$

(5)
one-frequency laser with $\Delta = -6\Gamma$, $s = 10$; (c) one-frequency laser with $\Delta = -6\Gamma$, $s = 10$.

FIG. 1: Force of diffuse lights vs atomic velocity: (a) two-frequency lasers with $\Delta_1 = -3\Gamma$, $\Delta_2 = -6\Gamma$, $s_1 = s_2 = 5$; (b) one-frequency laser with $\Delta = -3\Gamma$, $s = 10$; (c) one-frequency laser with $\Delta = -6\Gamma$, $s = 10$.

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\beta = 1/[1 + \sum_{n=1}^{2} \frac{s_n}{1 + 4(\Delta_n - kv \cos \theta_n)^2 / \Gamma^2}]. \tag{6}
\]

Here $s_1, \Delta_1$ and $s_2, \Delta_2$ are the on-resonant saturation parameters and detunings for laser 1 and laser 2 respectively, and we assume that $|\Delta_2| > |\Delta_1|$. Eq. (6) is valid for both $kv \geq |\Delta_1|$ and $kv < |\Delta_1|$. For atoms with velocity $v < |\Delta_1| / k$, the force is similar to the optical molasses [13]. Fig. 1 gives a plot of force on a two-level atom in diffuse lights, which is a combination of different velocity ranges. From the figure, we can see that for small detuning, the velocity capture range is small, while for large detuning, the force for small velocity is small, and thus it can not cool atoms to very low velocity. Only with the combination of two lasers with appropriate frequencies, the lights can cool atoms over wide velocity range to very low temperature, as shown in the solid line of Fig. 1.

Fig. 2 shows the experimental setup for two-frequency diffuse light cooling of atoms in an integrating sphere, similar to the one described in Ref. [6]. Two cooling lasers are locked at the transition $5^2S_{1/2}, F = 2 \rightarrow 5^2P_{3/2}, F' = 3$ of $^{87}$Rb and the frequencies are shifted by Acousto-Optic Modulators (AOMs). A weak repumping laser with total power of 4.7 mW, mixed with the cooling lasers, is locked to the transition $5^2S_{1/2}, F = 1 \rightarrow 5^2P_{3/2}, F' = 2$.

This repumping laser is used to pump the population trapped in the $5^2S_{1/2}, F = 1$ back to the cooling state $5^2S_{1/2}, F = 2$. All lasers are injected into an integrating sphere through two multi-mode fibers. Diffuse lights are formed inside the sphere when the lasers are multi-reflected by its inner surface whose reflectivity is 98% at 780 nm wavelength. Inside the integrating sphere, a glass cell with an inner diameter of 43 mm, mounted on a vacuum system of $10^{-7}$ Pa, is connected to a rubidium reservoir which is kept at room temperature and supplies the cell the rubidium vapor.

A very weak probe laser with power of 1 $\mu$W, locked at the transition $5^2S_{1/2}, F = 2 \rightarrow 5^2P_{3/2}, F' = 3$, is placed vertically. When cold atoms are accumulated in the glass cell during the cooling, an absorption of the probe beam is recorded. Since the cold atoms are saturated by cooling lasers, the recorded signal does not reflect the real absorption of the probe beam by the cold atoms [6]. In order to measure the undisturbed properties of the cold atoms, we need to switch off all cooling lasers when the absorption signal become stable.

Fig. 3 shows a typical absorption signal vs time. Here $\Delta_1 = -3\Gamma$ and $\Delta_2 = -5\Gamma$. Total power of the two-frequency diffuse laser lights in the integrating sphere is 80 mW. When no cooling laser lights are injected into the integrating sphere, the signal gives the absorption of the probe beam by background vapor (which is fairly small compared with absorption signal of cold atoms). After cooling lasers are turned on, the absorption of the probe beam by cold atoms are gradually increased until it is stable. The loss of cold atoms comes mainly from the drop by gravity after the atoms are cooled, and once the accumulation and loss are balanced, the number of the cold atoms in the cell is stable (absorption signal in Fig. 2 when $t < 0$). After the absorption signal is stable, we suddenly switch off the cooling lasers (at $t = 0$ in Fig. 2), but keep the repumping laser on. The absorption of the probe beam by cold atoms is suddenly increased because
they are no longer saturated by the cooling lights. The peak does give the real absorption signal of the probe beam by cold atoms. The quickly decreased absorption is due to the decreasing of the cold atom’s density, which is resulted from the momentum diffusion of cold atoms excited by the probe beam.

The absorption peak in Fig. 4 represents a real absorption of the probe beam for cold atoms in the glass cell, from which we can determine the number of cold atoms in the glass cell. Fig. 4 gives number of cooled atoms by two-frequency diffuse lights vs detuning $\Delta_2$ of laser 2 with fixed detuning $\Delta_1 = -3 \Gamma$ of laser 1. The two-frequency diffuse light cooling is equivalent to single-frequency diffuse light cooling when $\Delta_2 = \Delta_1$. In Ref. [6], we already proved that for single frequency diffuse cooling, the maximum number of cold atoms can be obtained when the detuning is around $-3 \Gamma$. In Fig. 4, when $\Delta_2 = \Delta_1 = -3 \Gamma$ the maximum number of cold atoms in single frequency diffuse light is obtained. As $\Delta_2$ increases, more atoms are cooled and accumulated, and maximum number of cold atoms reaches $3.9 \times 10^9$ when $\Delta_2 = -5 \Gamma$. This is a clear evidence of the increasing capture power of cold atoms in two-frequency diffuse lights.

Several factors limit the further increasing of cold atoms in the two-frequency diffuse lights. The number of the captured atoms depends on the number of atoms over the capture range of two-frequency diffuse light in the background vapor. After those atoms are cooled, the vapor atoms again become equilibrium through collision, and atoms over the capture range are produced again. The cycle keeps the cooling and capturing of atoms continuous until it is balanced to the loss of cold atoms discussed previously. Increasing the background vapor pressure can increase both the number of atoms over the capture range and collision between atoms, and thus can increase the captured cold atoms. Certainly, increasing the vapor pressure also increases the collision between hot atoms and cold atoms, which is a damage to the cold atoms.

In conclusion, we have demonstrated the increasing capture power of atoms in two-frequency diffuse lights, and discussed the possibility of further improvement. The increased number of cold atoms is useful for the improvement of an atomic clock using cold atoms in an integrating sphere.

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