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Increasing the cold atom density in an integrating spherical cavity

Yan-Ling Meng[a], Hua-Dong Cheng[a,*,1], Peng Liu[a], Ben-Chang Zheng[a], Ling Xiao[a], Jin-Yin Wan[a], Xiu-Mei Wang[a], Liang Liu[a,b,*,2]

[a] *Key Laboratory of Quantum Optics, Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800, China*

[b] *Key Laboratory of Atomic Frequency Standards, Wuhan Institute of Physics and Mathematics, Chinese Academy of Sciences, Wuhan 430071, China*

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ABSTRACT

A novel method of angled incidence for diffuse laser cooling of ^{87}Rb is presented to improve the distribution of cold atom density in an integrating sphere. The angled injection scheme could cool more atoms in the middle of the sphere compared to the previous normal injection scheme. The loading time of the cold atoms for the angled injection scheme is twice as that of the normal injection scheme. The SNR and the contrast of the detected signal would be improved in the angled injection scheme.

1. Introduction

Laser cooling of atoms is one of the most rapidly developing fields in the late 20th century. Cold atoms are widely used in the precise measurement of the internal structure of atoms and the fundamental physical constants [1,2]. These atoms have potential uses for the generation, manipulation, and storage of quantum state of light, thereby making them a promising resource in quantum information [3,4]. In addition, the performance of cold atom clocks has been greatly improved [5]. Several methods for laser cooling of atoms have been reported. Atoms can be cooled in optical molasses, as first realized by Steven Chu et al. [6], or by a Zeeman decelerator [7] to slow down an atomic beam. Magnetic optical trap [8] simplifies the process of cooling and trapping atoms with lasers. Compared with the above mentioned methods, integrating sphere cooling has simpler structure, occupies smaller volume, and does not require precise collimation in the cooling light [9]. These advantages make integrating sphere cooling an ideal cold atom source for compact and small apparatus. Furthermore, the apparatus for this method is an all-optical structure, which is favorable for magnetically sensitive applications.

The early reports on diffuse light cooling, which focus on the slowing of atomic beams, are in the 1990's [10–12]. HORACE project uses a polished spherical cavity and 6 cooling beams to produce the diffuse light for cooling atoms from the vapor background and reaches a stability of $2.2 \times 10^{-13}\tau^{-1/2}$ [13,14]. They think the cold atoms are not gathered in the center of the cavity, and can be pushed to the center by blue-detuned light. The volume for this clock is expected to be around 1 L to 2 L. Integrating sphere cooling is a primary key issue for atomic clocks with small volumes because the atoms can be cooled, prepared, interrogated, and detected at the same place.

The density distribution of cold atoms in the integrating sphere was measured in the previous work with the configuration of two normal incident cooling beams [15]. It shows that fewer cold atoms locate in the middle of the sphere, while maximum density appears in the region between the center and inner surface of the sphere. This density distribution is unfavorable for improving the SNR of the clock signal. Another study has shown that density distribution can be controlled to achieve a Gaussian density distribution in a cylindrical cavity [16]. However, spherical cavity is different from cylindrical cavity in geometry, and the method used in cylindrical cavity is not suitable for spherical cavity.

In this study, we propose an angled injection scheme with four cooling beams at the incident angle of 23° from the normal to avoid the incident light from passing through the center of the sphere, which is different from the previous normal injection schemes [9,13–16]. This new incident method can gather more

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[*] Corresponding authors at: Qinghe Rd No. 390, Jiading District, Shanghai, China.
E-mail addresses: chenghd@siom.ac.cn (H.-D. Cheng), liang.liu@siom.ac.cn (L. Liu).

[1] Tel.: +86 021 69918470; fax: +86 021 69918537.

[2] Tel.: +86 021 69918358; fax: +86 021 69918537.

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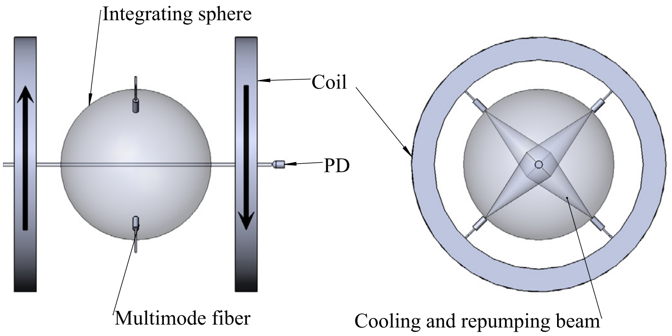

Fig. 1. Cooling and repumping light are injected into the sphere at normal incidence. Four multimode fibers are evenly set around the spherical cavity.

cold atoms in the middle of the sphere, which is beneficial for improving the SNR and the contrast of the detected signal. We also analyze the cooling efficiency for different values of cooling laser and repumping laser power and the loading rate of cold atoms.

2. Experimental results and discussion

The method of measuring density distribution of cold atoms was discussed in our previous paper [15]. As can be seen from Fig. 1, a pair of anti-Helmholtz coils was used to produce a quadrupole field. The integrating sphere was placed between the coils, and the quadrupole field split the Zeeman sublevels of the cold atoms and the energy shift was position dependent in the sphere. The σ^+ polarized probe beam tuned to the transition of $F = 2$ to $F' = 3$ for ^{87}Rb was resonant with the cold atoms located at the region of zero magnetic field. The coils were mounted onto a guide track and can be moved along it. The density distribution of cold atoms was obtained by moving the coils along the axis of the probe beam point by point.

Filled with Rubidium vapor, the integrating sphere was made of quartz and connected to an ion pump through a 15 mm diameter tube to maintain the background pressure at around 10^{-7} Pa. Its inner diameter is 100 mm. The surface of the sphere was sprayed with the reflective material Avian B from Avian Technologies with diffuse reflective index of >98% at 780 nm. An external-cavity, single mode diode laser (Toptica TA 100) was red detuned to the transition of $5^2S_{1/2}$, $F = 2$ to $5^2P_{3/2}$, $F' = 3$ to provide the 220 mW cooling light. Meanwhile, the 6 mW repumping light was frequency locked to the transition of $5^2S_{1/2}$, $F = 1$ to $5^2P_{3/2}$, $F' = 2$. The cooling light and repumping light were combined by a polarization beam splitter (PBS). Then they were evenly split into four parts and injected into the integrating sphere through four multimode fibers. The power of the circularly polarized probe beam was about 1 μW. The cooling time was set to 1.5 s, during which the cooling and repumping light were turned on simultaneously to cool the atoms. The magnetic field was activated immediately after the cooling and repumping light was shut off. And a few milliseconds later when the magnetic field was stable, the probe beam was turned on to detect the cold atoms.

In this work, we initially tested the first scheme, in which four laser beams were evenly set around the spherical cavity at normal incidence as shown in Fig. 1. The cooling light beams were injected into the cavity to yield diffuse light by multiple reflections on the inner surface of the cavity. Fig. 3 shows the density distribution along the axis of the probe beam (square). It can be seen that the distribution of cold atoms is not uniform, and the minimum appears in the center of the integrating sphere, which is similar to the previous result with two cooling beams [15]. In Figs. 3–6, each data point was obtained by averaging 30 measurements. The error bars are based on the standard deviation of the distribution for each data point.

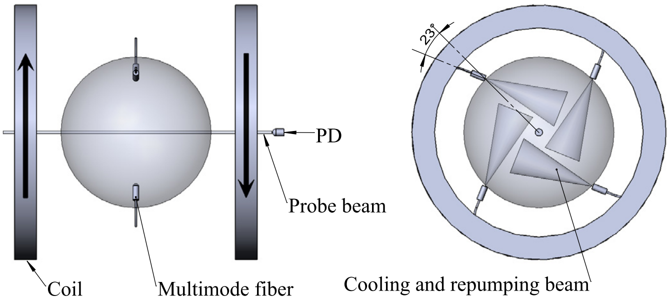

Fig. 2. Cooling and repumping light are injected into the sphere at an angle of about 23° from the normal.

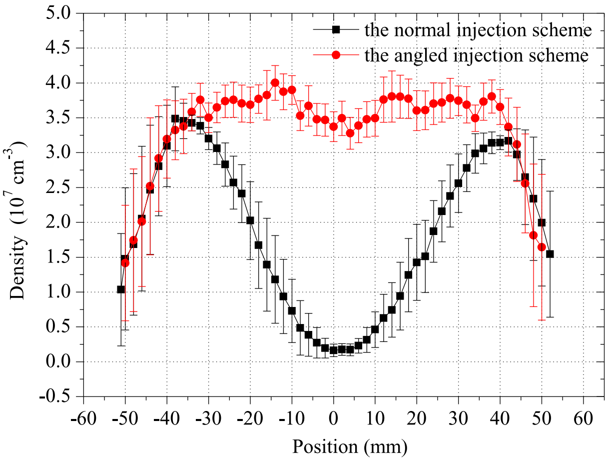

Fig. 3. Density distribution along the axis of the probe beam for the two schemes in Figs. 1 (square) and 2 (circle). The zero point corresponds to the center of the sphere.

The light inside the sphere consists of two parts: the injected travelling light and the diffuse light reflected by the inner surface of the sphere. The diffuse light can cool atoms effectively. However, four injected travelling lights cross in the central area of the integrating sphere and push the atoms away because of the unbalanced optical pressure, leading to fewer cold atoms in the middle of the integrating sphere.

For the second scheme, we injected the cooling lasers with an angle at about 23° from the normal (Fig. 2, the new injection method) to avoid the pushing effect in the first scheme. The numerical aperture of the multimode fiber is 0.22, which corresponds to a divergence angle of 12.7°. It's easy to calculate that if the incident angle is smaller than 16°, part of the injection light will still pass through the central region, thus pushing away the cold atoms. A large injection angle is also unfavorable. The reflection coefficient at the surface of quartz will increase if the incident angle is larger than 30 degrees based on Fresnel's equations for reflection and refraction. As a consequence the cooling laser power being reflected will become prominent. So the suitable range is between 16°–30°. Here we selected the angle of 23°.

The density distribution of cold atoms for the second scheme is also shown in Fig. 3 (circle). It can be seen that more cold atoms gathered in the middle of the sphere. The cold atoms' density distribution in the integrating sphere is determined by the distribution of the light field. Here the injected travelling lights did not traverse the central region of the integrating sphere, in which the cold atoms would not be pushed away. Therefore more atoms were captured by the diffuse light. Changing the incident angle generates a homogeneous light field in the central area of this sphere, thereby resulting in a homogeneous density distribution.

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