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An effective pumping method for increasing atomic utilization in a compact cold atom clock*

Xin-Chuan Ouyang(欧阳鑫川)[1,2], Bo-Wen Yang(杨博文)[1,2], Jian-Liao Deng(邓见辽)[1], Jin-Yin Wan(万金银)[1], Ling Xiao(肖玲)[1], Hang-Hang Qi(亓航航)[1,2], Qing-Qing Hu(胡青青)[3,†], and Hua-Dong Cheng(成华东)[1,2,‡]

[1] *Key Laboratory of Quantum Optics and Center of Cold Atom Physics, Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai* 201800, *China*

[2] *Center of Materials Science and Optoelectronics Engineering, University of Chinese Academy of Sciences, Beijing* 100049, *China*

[3] *Advanced Interdisciplinary Technology Research Center, National Innovation Institute of Defense Technology, Beijing* 100010, *China*

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We propose a simple pumping method to increase the effective population of cold atoms in the clock state and investigate the factors which affect the pumping efficiency in cold atom systems. We report the theory and demonstrate the corresponding experiment in an ^{87}Rb integrating sphere cold atom clock. The experimental results show that the population of cold atoms in the Zeeman sublevel $|F=2,m_F=0\rangle$ is approximately 1.62 times that of the result using optical pumping alone. This method can also be applied to increase the effective population in any one of the target Zeeman sublevels in other cold atom systems.

Keywords: optical pumping, Zeeman sublevels, atomic utilization

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1. Introduction

Preparation of an atomic ensemble in a single Zeeman sublevel state has been applied in many physics research fields, ranging from precision measurement[1–5] to quantum information science.[6–9] Several different techniques have been successfully used to pump atoms to a given Zeeman sublevel. In Ref. [10], a double-resonance technique combining laser optical pumping with RF transitions was used to move a ^{23}Na atom beam to a single hyperfine sublevel, which achieved a state purity of more than 90%. Boozer *et al.* used a method of incoherent Raman transitions to prepare a trapped cesium atomic cloud in a specific Zeeman state.[11] References [12,13] demonstrated the theory and experiment involving two-laser pumping of a cesium atom beam to a specific Zeeman sublevel. Later, Di Domenico *et al*. applied the two-laser optical pumping technique to a continuous atomic fountain to improve the signal-to-noise ratio of clock transition.[14] In Refs. [15,16], a method involving combining optical and radio pulses with pumping atoms was proposed.

In this paper, we propose a simple optical-plus-microwave pumping method which only needs the time sequence of the system to be changed, and we investigate the factors affecting the pumping efficiency of cold atoms in gas chambers. The experiments are performed in an integrating sphere cold atom clock (ISCAC) system and can be easily extended to other systems, such as atom fountains and other compact cold atom clocks. The atomic population in the clock state of $|2,0\rangle$ ($|F=2,m_F=0\rangle$, the same as below) is increased to 1.62 times that of the result using optical pumping alone. We establish the theoretical model to analyze the factors which affect the pumping efficiency.

2. Experimental scheme and theory

A schematic of the ISCAC is shown in Fig. 1, and for a detailed description the reader can refer to our previous work.[17] The microwave cavity with a resonance frequency of the ^{87}Rb ground-state hyper-fine transition (6.834 GHz) is placed in a vacuum chamber. The biased magnetic field (approximately 6 mG), which is parallel to the axis of the microwave cavity, undegenerates the Zeeman levels and provides the quantization axis. Five layers of magnetic shields are added to minimize the influence of the geomagnetic field. The optical system includes the cooling ($\sim$ 120 mW), repumping ($\sim$ 10 mW), and pumping ($\sim$ 0.6 mW), as well as probe lights ($\sim$ 1.6 μW), and the first three lights are injected into the microwave cavity through four multimode fibers and then reflected by the inner surface of the cavity to produce the diffuse light. The cold atoms are detected by the retro-reflected probe light. The typical time sequence of the ISCAC includes four steps (shown in Fig. 2(a)): cooling atoms, optical pumping to the $F=1$ state, Ramsey microwave interrogation (from $|1,0\rangle$ to $|2,0\rangle$), and optical detection of the population in the $|2,0\rangle$ state.

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†Corresponding author. E-mail: qqhu@baqis.ac.cn

‡Corresponding author. E-mail: chenghd@siom.ac.cn

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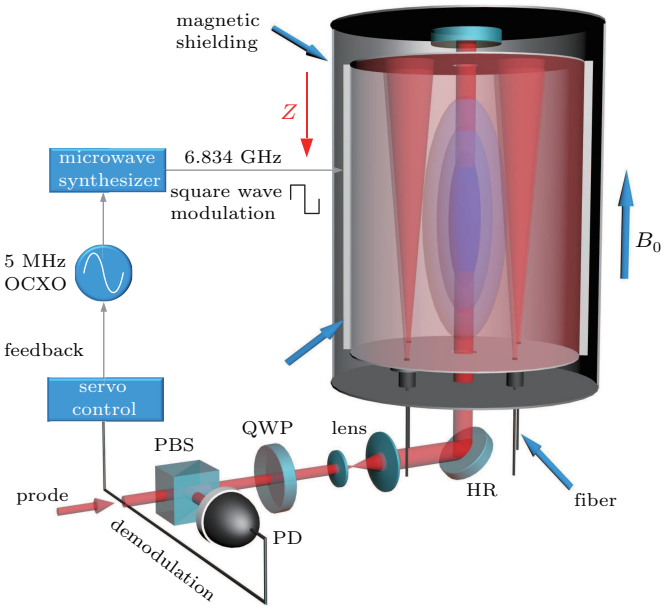


Fig. 1. A schematic of the ISCAC. HR: highly reflective mirror; QWP: quarter-wave plate; PBS: polarizing beam splitter; PD: photodetector.

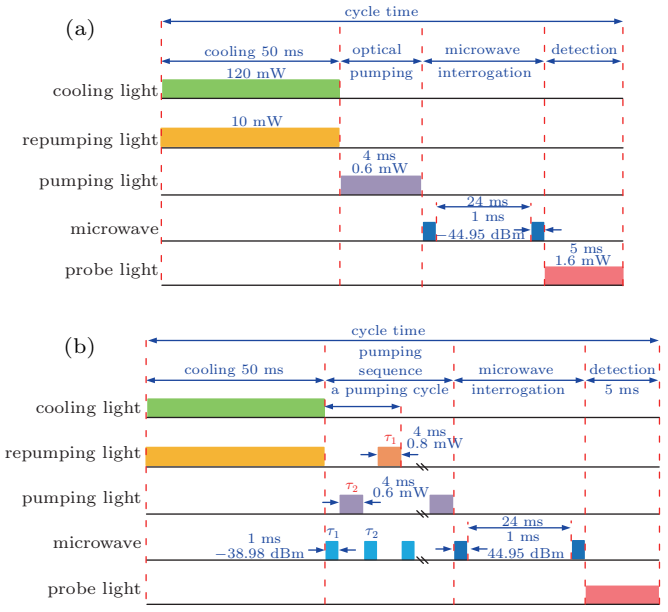


Fig. 2. The time sequence of the ISCAC. (a) Optical pumping alone. (b) Optical-plus-microwave pumping.

After the cooling phase, nearly all atoms are prepared in the $F = 2$ sublevel state. The optical-plus-microwave pumping progress, as shown in Fig. 2(b), is used to increase the populations in the clock state. A pumping cycle consists of four steps. Firstly, the atoms in the $|2,0\rangle$ state are stimulated to transition to the $|1,0\rangle$ state by a microwave π pulse (duration of 1 ms, -38.98 dBm) with frequency resonant with $|1,0\rangle \rightarrow |2,0\rangle$. Secondly, the atoms remaining in the $F = 2$ magnetically sensitive sublevel states are optically pumped (duration of 4 ms, 0.6 mW) to the $F = 1$ state to increase the population of the $|1,0\rangle$ clock state. Thirdly, the resonant microwave π pulse is added again to stimulate transition of the atoms in the $|1,0\rangle$ state to the $|2,0\rangle$ state. Finally, the repumping light (duration of 4 ms, 0.8 mW) excites the $F = 1 \rightarrow F' = 2$ transition to increase the population of atoms in the $|2,0\rangle$ state further. The state evolution progress of the atom population during the pumping cycle is shown in Fig. 3. When applying this method in an atomic clock, the pumping cycle should stop at step 2.

To simulate the optical pumping processes, the involved thirteen sublevels of ^{87}Rb, as shown in Fig. 3, are considered. The repumping and pumping lasers are chosen to be resonant with the transition of $F = 1 \rightarrow F' = 2$ and $F = 2 \rightarrow F' = 2$, respectively. We assume that the optical pumping process does not involve the other levels of the D_2 line. We utilize three equal-intensity linearly polarized lights in three orthogonal directions to simulate the isotropic pumping effect of the diffuse light. After the cooling phase, the microwave cavity can be regarded as a gas chamber full of cold atoms, and the motion of cold atoms needs to be considered. The evolution of the density matrix for atoms during the pumping phase is given by the Liouville equation

$$\dot{\rho} = \frac{1}{\mathrm{i}h}[H,\rho] - \frac{1}{2}\{\hat{\Gamma},\rho\} + \Lambda + \mathrm{Tr}F\rho, \tag{1}$$

where H is the total Hamiltonian, and $\hat{\Gamma}$ is the relaxation matrix, which describes relaxation induced by the spontaneous decay and atom losses caused by the motion of atoms in the radial direction of the microwave cavity going beyond the detection region and the gravity. Normally, the collisions[18] between cold atoms and the background gas and the decoherence[19] of the Zeeman sublevels are relatively small compared to the former factors. Here, Λ is the repopulation matrix, which describes the movement of atoms from outside into the detection region, and F is the spontaneous emission operator. The Hamiltonian H is the sum of several contributions, which is written as

$$H = H_0 + H_\mathrm{p} + H_\mathrm{rp} + H_\mathrm{mw}, \tag{2}$$

where H_0 is the unperturbed Hamiltonian, which includes the static contribution of the linear Zeeman effect, H_p is the interaction with the pumping light, H_rp describes the interaction with the repumping laser field, and H_mw is the interaction with the microwave field. The specific description of the Hamiltonian is as follows:

(i) To pump and repump light, we use a generic matrix element of the Hamiltonian H_E to describe them. With the Wigner–Eckart theorem,[20] it can be simplified as

$$\begin{aligned}\langle F,m_F|H_E|F',m_{F'}\rangle &= \frac{E}{\hbar}\sum_q \varepsilon_q \langle F,m_F|d_q|F',m_{F'}\rangle \\ &= A\left(F,m_F;F',m_{F'}\right)\Omega\cos\omega t,\end{aligned} \tag{3}$$

where d_q is the electric dipole operator, ε_q is the polarization component which is defined as

$$\varepsilon_1 = -\frac{1}{\sqrt{2}}(1+\mathrm{i}),\ \ \varepsilon_0 = 1,\ \ \varepsilon_{-1} = \frac{1}{\sqrt{2}}(1-\mathrm{i}), \tag{4}$$

Ω is the laser Rabi frequency and is defined as

$$\Omega = \frac{E\left\langle 5S_{1/2}\right| d \left|5P_{3/2}\right\rangle}{\hbar}, \tag{5}$$

and $A\left(F,m_F;F',m_{F'}\right)$ is defined as

$$A\left(F,m_F;F',m_{F'}\right) = \sum_q \varepsilon_q (-1)^{2F-m_F} \sqrt{(2F+1)(2F'+1)} \times \begin{pmatrix} F & 1 & F' \\ -m_F & q & m_F \end{pmatrix} \begin{Bmatrix} 3/2 & 3/2 & F' \\ 1 & F & 1/2 \end{Bmatrix}, \tag{6}$$

where the coefficients in round and curly brackets are the $3-j$ and $6-j$ symbols, respectively.

(ii) We assume that radial distribution of the microwave magnetic field in the cavity is uniform since we focus on the small detection region near the cavity axis. For the TE_{011} mode of the cavity, the interaction of the Hamiltonian with the microwave field in the cavity is given by

$$H_{\rm mw} = \frac{\mu_{\rm B}}{\hbar}\left(g_S S + g_I I\right)\cdot B \sin\frac{\pi z}{L}\cos\omega t, \tag{7}$$

where g_F is the Lande g-factor, $\mu_{\rm B}$ is the Bohr magneton, and L is the inner height of the microwave cavity. After the cooling phase, the atom-ensemble density distribution is non-uniform on the axis of the microwave cavity. According to Ref [21], we obtain a polynomial function $f(z)$ of cold atom distribution by fitting the atomic density data (shown in Fig. 4), which is written as

$$f(z) = 2.46 + 0.596\cdot z - 0.0295\cdot z^2 + 6.31\times 10^{-4}\cdot z^3 - 5.26\times 10^{-6}\cdot z^4. \tag{8}$$

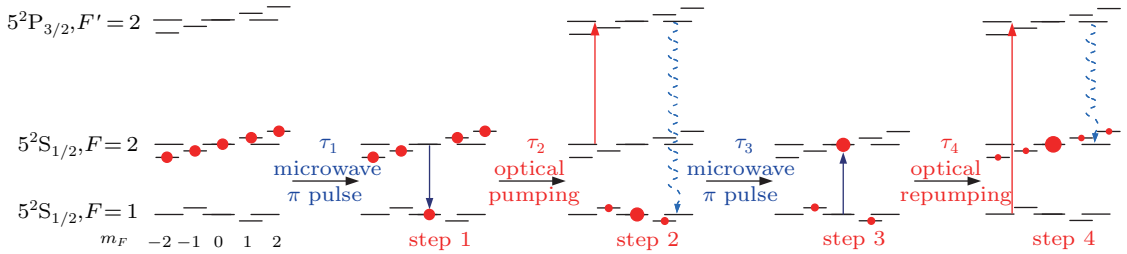


Fig. 3. The state evolution progress of the atom population during the pumping cycle. The dark blue line, red line, and light-blue dotted line represent the microwave pumping, optical pumping and spontaneous, respectively.

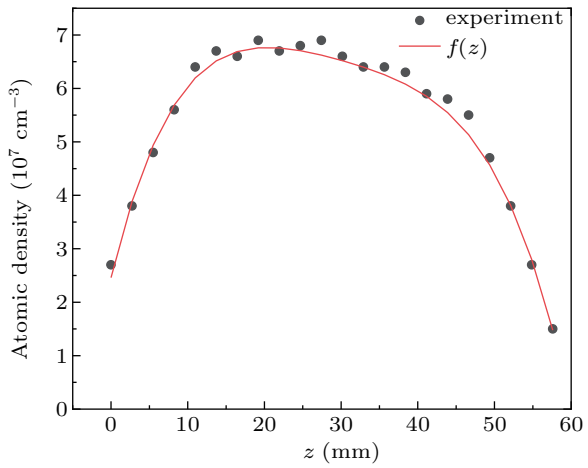


Fig. 4. Distribution of the atom-ensemble density along the axis of the cavity.

Cold atoms experience different amplitudes and phases of the microwave field in different positions along the axis because of the nonuniformity of the microwave field. There is an optimal amplitude and duration of the microwave pulse which can stimulate the transition of most of the atoms in the $|1,0\rangle$ state to the $|2,0\rangle$ state. We call this microwave pulse the equivalent π pulse.

The last term $(\mathrm{Tr}F\rho)$ in Eq. (1) describes the repopulation of ground states due to spontaneous decay, which is given by

$$\begin{aligned}\left\langle F,m_1\right|\mathrm{Tr}F\rho\left|F,m_2\right\rangle &= \mathrm{Tr}F_{m_1m_2}\rho \\ &= \frac{4\omega^3}{3\hbar c^3}\sum_{m_1'm_2'}\sum_q (-1)^q \left\langle F,m_1\right| d_q \left|F',m_1'\right\rangle \\ &\quad\times\left\langle F',m_2'\right| d_{-q}\left|F,m_2\right\rangle \rho_{F'm_1',F'm_2'} \\ &= \Gamma\sum_{m_1'm_2'} B\left(F,m_1;F\prime,m_1';F,m_2;F\prime,m_2'\right) \\ &\quad\times\rho_{F'm_1',F'm_2'},\end{aligned} \tag{9}$$

where F denotes the ground state, F' denotes the excited state, ω is the atomic transition frequency of the D_2 line, $\hbar$ is the Planck constant, c is the speed of light, and the spontaneous decay rate Γ is written as

$$\Gamma = \frac{4\omega^3}{3\hbar c^3}\frac{1}{4}\left|\left\langle 5S_{1/2}\right| d \left|5P_{3/2}\right\rangle\right|^2 \tag{10}$$

and the coefficient $B\left(F,m_1;F',m_1';F,m_2;F',m_2'\right)$ is defined as

$$\begin{aligned}&B\left(F,m_1;F',m_1';F,m_2;F',m_2'\right) \\ &= \sum_q (-1)^{2F-m_1-m_2}\, 4\,(2F+1)\left(2F'+1\right) \\ &\quad\times\begin{pmatrix} F & 1 & F' \\ -m_1 & q & m_1' \end{pmatrix}\begin{pmatrix} F & 1 & F' \\ -m_2 & q & m_2' \end{pmatrix} \\ &\quad\times\begin{Bmatrix} 3/2 & 3/2 & F' \\ 1 & F & 1/2 \end{Bmatrix}^2.\end{aligned} \tag{11}$$

For theoretical calculations, all the atoms are assumed to be distributed evenly in the $|F=2,m_F=0,\pm1,\pm2\rangle$ states at the beginning. We assign the experimental time sequence of the pumping light, repumping light, and microwave interrogation into the corresponding Hamiltonian in Eq. (2). Thus, the probability of atoms in clock states with different pumping cycles can be evaluated by Eq. (1). Since all the atoms within the probe laser beam can be detected, the average probability

of the atom in the state $|i,j\rangle$ can be normalized as

$$\tilde{\rho}_{i,j} = \frac{\int_0^L \rho_{i,j}(z) f(z)\,\mathrm{d}z}{\int_0^L f(z)\,\mathrm{d}z}, \tag{12}$$

where $\rho_{i,j}(z)$ is the probability of the atoms staying in the state of $|i,j\rangle$ at the position z, and L (~ 57.6 mm) is the inner height of the microwave cavity.

3. Experimental and theoretical results

In the experiment, we choose a microwave pulse duration of 1 ms to stimulate the atoms during the pumping phase. The corresponding power of the microwave for the equivalent π pulse is -38.98 dBm. The Rabi oscillations with different pumping sequences are shown in Fig. 5(a). According to the amplitude of the Rabi oscillations, the number of cold atoms can be estimated with the equation[22]

$$N = \frac{\pi r^2}{\sigma_0}\left[\frac{I_0 - I_t}{I_s} + \left(\frac{4\delta^2}{K^2}+1\right)\ln\left(\frac{I_0}{I_t}\right)\right], \tag{13}$$

where r is the radius of the probe beam, and σ_0 is the resonant cross-sectional area. I_0 and I_t are the probe light intensity before and after going through the physical package, respectively. Here, δ is the detuning of the probe light from the resonance frequency of $F=2$ to $F'=3$, K is the natural linewidth of the ^{87}Rb D_2 line transition, and I_s is the on-resonance saturation intensity.

The normalized experimental results obtained using Eq. (13) are then compared with the results of the theoretical calculation using Eq. (12), as shown in Fig. 5(b). The experimental results show that after seven microwave π pulses, the number of cold atoms in the $|2,0\rangle$ state is about 1.62 times that of the result using optical pumping only. However, the atomic population in the clock state increases gradually (rather than linearly) with the number of microwave π pulses. According to the results of theoretical calculations, approximately 65% of the atoms should be populated in the $|1,0\rangle$ state after seven microwave pumping pulses. However, only about 46% of the atoms are excited to the $|2,0\rangle$ state according to the experimental results. We attribute this decrease in the state transfer efficiency to the following.

Firstly, a mechanical shutter[23] based on a stepper motor is used in the optical path to prevent the light leakage in order to avoid any temporal overlap between the pumping light pulse, microwave pulse, and repumping light pulse during the pumping phase. However, the large turn-on and turn-off delays of the mechanical shutter increase the total time of the pumping sequence. As the number of π-pulses increases, the pumping period becomes longer, which leads to a reduction in the total number of cold atoms.

Secondly, the equivalent microwave π pulse cannot completely invert the atom population between the two clock states of $|1,0\rangle$ and $|2,0\rangle$. Therefore, as the number of pumping pulses increases, the residual atoms in $|2,0\rangle$ (step 1) and $|1,0\rangle$ (step 3) states during the pumping phase (shown in Fig. 3) will increase, which leads to a decrease in the pumping efficiency.

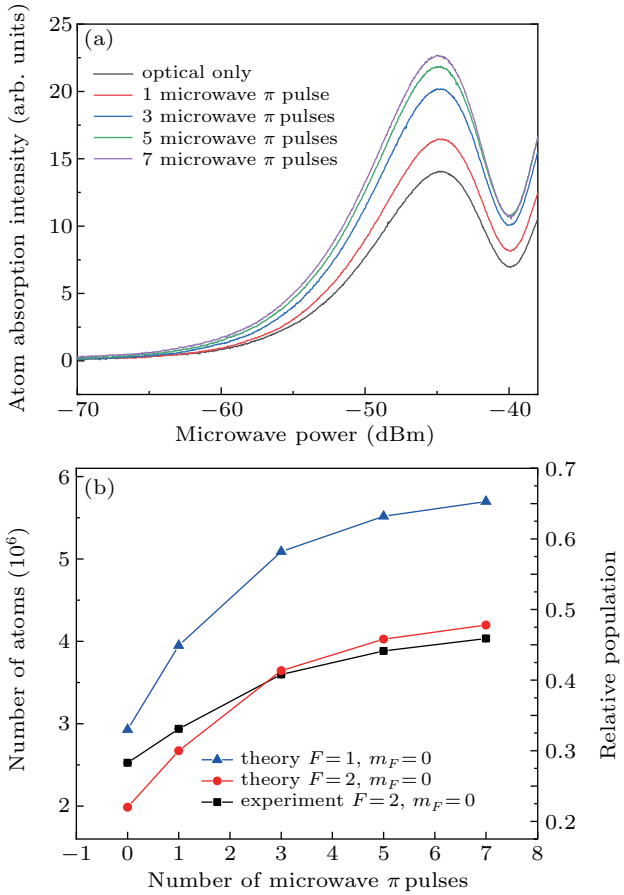


Fig. 5. (a) Rabi oscillations for different pumping pulses. (b) The number and relative population of atoms in the clock state with different pumping pulses. The squares represent the experimental results. The circles and triangles represent theoretical results for the atom populations in the $|2,0\rangle$ state and $|1,0\rangle$ state, respectively.

Considering the probe light detects all the atoms in the $F=2$ states and that some atoms in the $|1,\pm1\rangle$ states are stimulated to transition to the $|2,\pm1\rangle$ states during the Rabi interrogation, the experimentally measured atom number is larger than the theoretically calculated results when the number of π-pulses is small, as shown in Fig. 5(b). As the number of π-pulses increases, the atoms in the $|1,\pm1\rangle$ states decrease, so the difference between the theoretical and experimental results decreases. Besides, some deviation between the theoretical and experimental results still exists because the three equal-intensity linearly polarized lights cannot perfectly simulate the pumping effects of the diffuse light. The relationship between the contributions of atomic noise to the frequency stability of the atomic clock and the number of atoms can be written as[24]

$$\sigma_{N_{\mathrm{atom}}} \sim \sqrt{T_c/N_{\mathrm{atom}}}, \tag{14}$$

where T_c is the cycle duration of a clock operation and N_{atom} is the number of atoms in the clock state. The key to applying this method to an atomic clock is to select an appropriate

number of pumping cycles, because both N_{atom} and T_c increase with the number of pumping cycles. Besides, the Dick effect also increases with the number of pumping cycles.

4. Conclusion

We proposed a simple pumping method to increase the number of cold atoms in the clock state. The theoretical and experimental results have demonstrated that the number of atoms in the $|2,0\rangle$ state could be increased to 1.62 times that of the result using optical pumping only. This pumping method requires one to invert the atom population between the $|1,0\rangle$ and $|2,0\rangle$ states several times. In our system, the turn-on and turn-off delays of the mechanical shutter are as large as 4 ms, which increases the total time of the pumping cycle. Moreover, the atomic distribution is not relatively concentrated and the microwave field inside the microwave cavity is non-uniform, which leads to the incomplete flip of the atomic number between the two clock states of $|1,0\rangle$ and $|2,0\rangle$ when using a microwave π pulse, and finally reduces the total pumping efficiency. Therefore, the efficiency of this pumping method could be increased further by improving the response speed of the optical switch to decrease the pumping cycle's duration, and by enhancing the uniformity of the magnetic field in the microwave cavity to increase the reverse efficiency of the atoms between Zeeman sublevels. Moreover, this method could be applied to other cold atom systems very easily to prepare atoms in any specific Zeeman sublevels.

References

[1] Chen Y, Zuo G H, Tian Z Z, Zhang Y C and Zhang T C 2019 *Chin. Phys. B* **28** 117601

[2] Gillot P, Francis O, Landragin A, Dos Santos F P and Merlet S 2014 *Metrologia* 51 L15

[3] Gustavson T L, Bouyer P and Kasevich M A 1997 *Phys. Rev. Lett.* **78** 2046

[4] Hart M W, Hammond M S, Dunning F B and Walters G K 1989 *Phys. Rev. B* **39** 5488

[5] Lamoreaux S K, Jacobs J P, Heckel B R, Raab F J and Fortson E N 1986 *Phys. Rev. Lett.* **57** 3125

[6] Chou C W, Laurat J, Deng H, Choi K S, De Riedmatten H, Felinto D and Kimble H J 2007 *Science* **316** 1316

[7] Cirac J I, Zoller P, Kimble H J and Mabuchi H 1997 *Phys. Rev. Lett.* **78** 3221

[8] Leibfried D, Blatt R, Monroe C and Wineland D 2003 *Rev. Mod. Phys.* **75** 281

[9] Li M M, Tan X S, Dai K Z, Zhao P, Yu H F and Yu Y 2018 *Chin. Phys. B* **27** 063202

[10] Dreves W, Jansch H, Koch E and Fick D 1983 *Phys. Rev. Lett.* **50** 1759

[11] Boozer A D, Miller R, Northup T E, Boca A and Kimble H J 2007 *Phys. Rev. A* **76** 063401

[12] Avila G, Giordano V, Candelier V, Declercq E, Theobald G and Cerez P 1987 *Phys. Rev. A* **36** 3719

[13] Tremblay P and Jacques C 1990 *Phys. Rev. A* **41** 4989

[14] Di Domenico G, Devenoges L, Dumas C and Thomann P 2010 *Phys. Rev. A* **82** 053417

[15] Bhaskar N D 1993 *Phys. Rev. A* 47 R4559

[16] Micalizio S, Godone A, Levi F and Calosso C 2009 *Phys. Rev. A* **80** 023419

[17] Liu P, Meng Y, Wan J, Wang X, Wang Y, Xiao L, Cheng H and Liu L 2015 *Phys. Rev. A* **92** 062101

[18] Newbury N R, Myatt C J and Wieman C E 1995 *Phys. Rev. A* 51 R2680

[19] Micalizio S, Godone A, Levi F and Calosso C 2009 *Phys. Rev. A* **79** 013403

[20] Edmonds A R and Mendlowitz H 1958 *Phys. Today* **11** 34

[21] Meng Y L, Cheng H D, Zheng B C, Wang X C, Xiao L and Liu L 2013 *Chin. Phys. Lett.* **30** 063701

[22] Mcdonald G D 2009 *Detecting Atomic Shot Noise On Ultra-cold Atom Clouds* (Bachelor) (Canberra: The Australian National University) (in Australia)

[23] Yu M, Xu B, Ouyang X, Wang X, Wan J, Xiao L, Cheng H and Liu L 2019 *Chin. J. Lasers* **46** 0804003

[24] Esnault F X, Rossetto N, Holleville D, Delporte J and Dimarcq N 2011 *Adv. Space Res.* **47** 854