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Dependence of the ^{85}Rb coherent population trapping resonance characteristic on the pressure of N_2 buffer gas*

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In order to exploit its potential applications, we experimentally study the dependence of ^{85}Rb-based coherent population trapping (CPT) resonance on N_2 buffer gas with 6 vapor cells filled with natural rubidium and N_2. The experiments are carried out at different pressures and temperatures, and the results reveal that higher cell temperature makes the resonance more sensitive to N_2 pressure. Thus, it is important to choose a proper buffer gas pressure at a given cell temperature. This work provides valuable data for the application of ^{85}Rb CPT resonance with a buffer gas of N_2.

Keywords: coherent population trapping (CPT), buffer gas, atomic clock

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1. Introduction

Coherent population trapping (CPT) due to the narrow resonance has been applied to the development of atomic clocks, magnetometers, etc. Applying the micro-electro-mechanical-systems (MEMS) technique, CPT-based atomic clocks and magnetometers can be potentially fabricated into chip-scale devices, and have advantages including small size and low power consumption, which make them very promising for portable devices.[1–10] Many studies have been carried out in the relevant fields, and our group has also made some progress on the CPT atomic clock[11–13] and CPT magnetometer.[14,15]

In applications, the prevailing implemented scheme normally employs a vertical cavity surface emitted laser (VCSEL) to provide lasing, and a microwave is mixed into the injection current of the VCSEL. Thus, its output is frequency-modulated (FM). To generate CPT resonance, two of the frequency components of the output are utilized to interact with alkali atoms through the Λ configuration, which consequently couples two hyperfine ground states to one excited state. The most generally used alkali atoms are ^{87}Rb and ^{133}Cs, and some other atoms are also candidates for CPT resonance. For instance, Goka *et al.*[16] and Liu *et al.*[17] developed CPT atomic clocks with ^{85}Rb. Generally, for higher frequency of the generated microwave, more power is required for electrical circuits. Compared with 6.8-GHz ground-state hyperfine splittings of ^{87}Rb and 9.2-GHz ones of ^{133}Cs, less power is needed for ^{85}Rb with 3.0-GHz hyperfine splittings. Besides, ^{85}Rb-based CPT resonance[16,17] was conveniently realized with natural rubidium, while for ^{87}Rb expensive isotopic samples were commonly used, as the isotope abundances of ^{85}Rb and ^{87}Rb in natural rubidium are 72% and 28%, respectively.

In most cases, the CPT resonance is excited in an atomic vapor cell, and the main decoherence originates from collisions between atoms and the cell wall. At room temperature, it can be suppressed as a result of elastic collisions by using an antirelaxation surface coating. The most effective and widely used coating is paraffin.[18] However, the cell size is generally small in the passive CPT atomic clock and in order to evaporate enough atoms the cell temperature is usually over 60 °C, the melting point of paraffin.[19] Therefore, filling the cell with a buffer gas of a certain density, which also collides with atoms elastically, is the most common method used to prevent collisions. Moreover, buffer gas confines the motion range of alkali atoms, which increases light–atom interaction time, thus enhancing the CPT resonance.

Inert gases were frequently used as buffer gases, and some other gases such as H_2, N_2, and CH_4 were also used. Especially, N_2 is suitable for CPT resonance with rubidium. In order to explore the potential applications of ^{85}Rb CPT resonance with N_2 as buffer gas, we experimentally study the CPT resonance behaviors with ^{85}Rb at different N_2 pressures, including frequency shift, linewidth, contrast, and correction slope.

2. Experiment

Figure 1 illustrates our experimental setup. The glass cell is filled with natural rubidium and buffer gas N_2. The solenoid generates about 2.57-μT magnetic field which provides a quantum axis for the system, and two $m_F = 0$ Zeeman levels of the ground states for the CPT resonance are selected. Outside the cell and solenoid, a permalloy shell shields stray fields and electro-magnetic radiations from the environment. The VCSEL provides a 794.7-nm-wavelength

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100-MHz-bandwidth linearly-polarized divergent laser beam, then it turns into a circularly-polarized $\Phi = 1$ mm parallel one by the lens and $\lambda/4$ wave plate. A neutral density (ND) filter is arranged as an attenuator to adjust the light intensity.

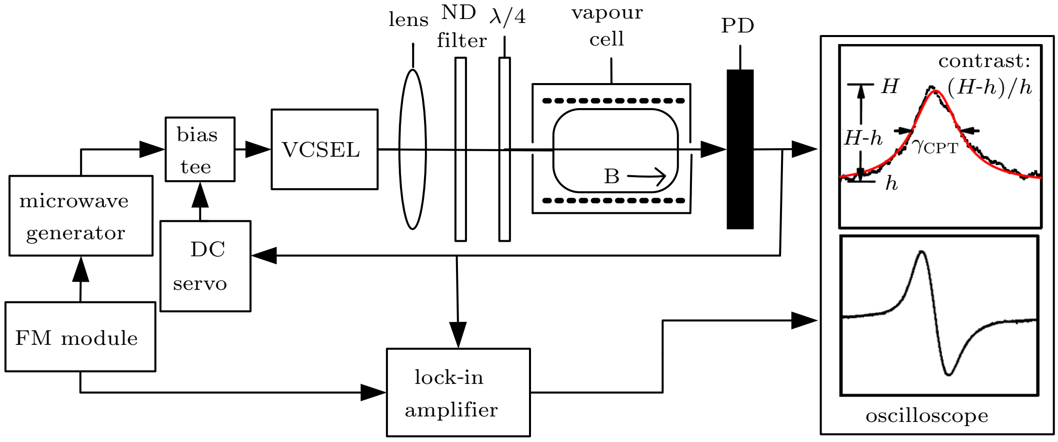

Fig. 1. (color online) Experimental setup. The typical CPT signal and demodulation results are shown by the curves on the oscilloscope. A Lorentzian line (red line) is fitted to the CPT signal.

A microwave generator (Agilent E8257D) provides a 1.517-GHz microwave ($\nu = \nu_{\rm hfs}/2 \approx 1.517$, $\nu_{\rm hfs}$ is the ground-state hyperfine splitting frequency of ^{85}Rb), which is mixed into DC injection current through the bias tee. Driven by the modulated current from bias tee, the VCSEL outputs a multi-chromatic laser. In this experiment, its ± 1 sidebands are used to probe the transitions of $|5S_{1/2}, F = 2, m_F = 0\rangle$ and $|5S_{1/2}, F = 3, m_F = 0\rangle$ states to $|5P_{1/2}, F', m_F = 1\rangle$ state, the Λ configuration, to achieve CPT resonance. Monitored with an FP etalon, the intensity of the ± 1 sideband lights is adjusted to the maximum when the microwave generator output power is -7 dBm.

After interacting with atoms, a photo detector (PD) behind the cell detects the transmitting laser. From the PD output, the Doppler-broadened transition spectral lines and electromagnetically induced transparency (EIT) spectral lines are separately extracted and processed. The Doppler-broadened spectral lines corresponding to transitions of $|5S_{1/2}, F = 2, m_F = 0\rangle$ and $|5S_{1/2}, F = 3, m_F = 0\rangle$ to $|5P_{1/2}, F', m_F = 1\rangle$ is chosen as the laser frequency discrimination signal, which is extracted and converted into the frequency error signal by using a homemade direct current servo (DC servo) circuit and mixed into the injection current of VCSEL for laser frequency stabilization. The microwave's frequency is modulated at 136 Hz with a modulation depth of 100 Hz by using a homemade FM module, and the EIT signal is phase-sensitive demodulated with a lock-in amplifier (SIGNAL RECOVERY model 7265).

We have prepared 6 atomic vapor cells for this experimental research, and the length and diameter of the cells are 0.8 cm and 2.5 cm, respectively. Besides natural rubidium, the cells are separately filled with N_2 at pressure of 2660, 3330, 3660, 3990, 4660, and 6650 Pa. Under the experimental temperature, the partial pressure of rubidium, about 10^{-4} Pa,[20] can be neglected after comparing with that of N_2.

3. Results and discussion

In atomic clock applications, it is important to reduce the frequency shift of CPT spectral line. The mainly involved frequency shifts are Zeeman shift, buffer-gas shift, light shift, and spin-exchange shift. In order to reduce the Zeeman shift effect, $|5S_{1/2}, F = 2, m_F = 0\rangle$ and $|5S_{1/2}, F = 3, m_F = 0\rangle$ states (0–0 states) are chosen to eliminate the linear Zeeman shift. At the experimental magnetic field of 2.57 μT, the remained quadratic Zeeman shift is only about 0.8 Hz.[21] The common light intensities will cause light of a few hundred Hertz to shift to atomic spectral lines.[22] Therefore, light shift normally will cause the CPT signal to have a few Hertz uncertainty caused by the light intensity fluctuation. As the populations of 0–0 states are basically equal, the spin-exchange shift is very small.[23,24] All the above-discussed shifts could be considered to be independent of buffer-gas pressure and temperature in comparison to the buffer-gas shift.

At three different temperatures, we experimentally measure frequency shifts of the CPT spectral line at six different N_2 pressures. Since the pressure change is actually small according to the temperature difference, it is ignored in the experiment, and figure 2 presents the experimental results. It is seen that the shift is basically proportional to N_2 pressure, fitting well with the linear function. The pressure coefficients are 1720 Hz/kPa for 43 °C, 1740 Hz/kPa for 50 °C, and 1750 Hz/kPa for 66 °C. The linear pressure coefficient supports the results of Refs. [25] and [26], and the coefficient is almost insensitive to temperature in our experimental range.

The CPT resonance signal is determined by the Lorentz line shape, and its full width at half maximum (FWHM) can be written as follows:[27]

$$\gamma_{\rm CPT} = \gamma_2 + \omega_R^2/\Gamma, \tag{1}$$

where γ_2 is the ground-state coherent relaxation rate, which is caused by collisions of ^{85}Rb with buffer gas, cell wall, etc, Γ is the excited-state coherent relaxation rate of atoms, which is caused by spontaneous decay of excited states and collision decay of buffer gas, and ω_R is the optical Rabi frequency. Equation (1) shows that the CPT resonance linewidth is proportional to the light intensity. The inset in Fig. 3 shows the relation of linewidth to the laser power measured with one of the cells (2660 Pa, N_2) in the experiment, which is in good agreement with the linear dependence of linewidth on light power. By fitting with Eq. (1), the obtained broadening rate is 7.5 Hz/μW, and γ_2 is about 161.5 Hz.

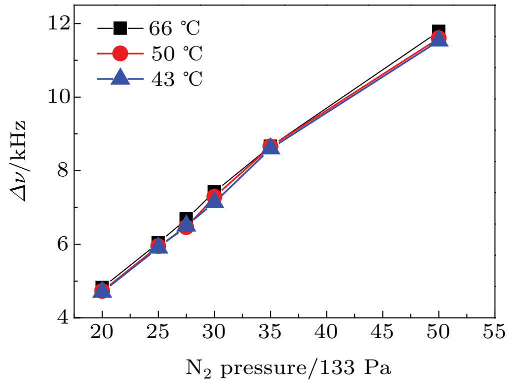

Fig. 2. (color online) Frequency shift of the 0–0 resonance from the unperturbed ground state hyperfine splitting frequency of ^{85}Rb as a function of N_2 pressure. $\Delta\nu = 2\nu - 3035732$ (kHz), where ν is the injection modulation frequency of VCSEL measured at the zero crossing of phase-sensitive demodulation result.

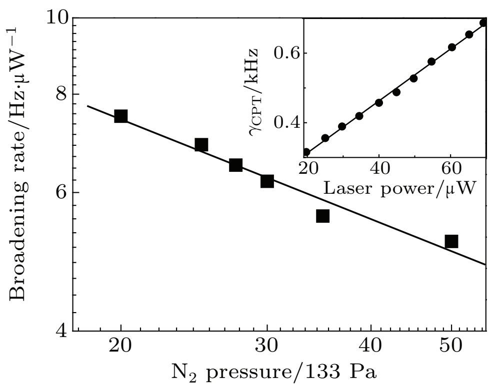

Fig. 3. Linear broadening rate of CPT resonance to laser power as a function of N_2 pressure measured at 66 °C and laser intensity of 8.18 mW/cm^2. The solid line represents the linear fitting result in logarithm. Inset shows the full width of CPT resonance measured at 66 °C as a function of laser power with N_2 pressure of 2660 Pa.

During CPT state preparation, a certain number of ^{85}Rb atoms will be pumped into spin-polarized dark state,[28] which reduces the number of working atoms for CPT resonance. Besides preventing collision, an additional contribution of buffer gas is repopulation collision which transfers certain spin-polarized dark state atoms back to the 0–0 state. Therefore, the relationship between linewidth and laser power varies at different buffer gas pressures. Figure 3 presents our experimental results. It is seen that in logarithm coordinate the broadening rate approximately linearly decreases with N_2 pressure increasing, and the tendency agrees with that in the study of other buffer gas.[29]

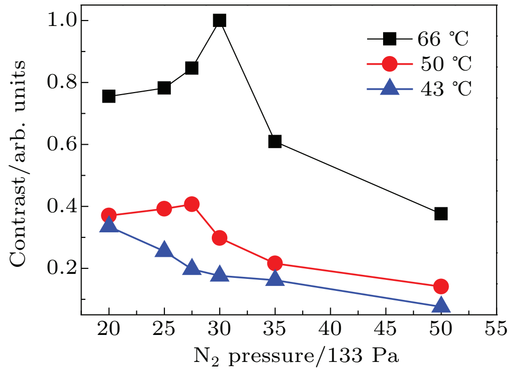

Fig. 4. (color online) Plots of CPT signal contrast versus N_2 pressure at laser intensity of 8.18 mW/cm^2.

In the experiment, after interacting with atoms, the laser beam is detected by a photo detector, and the signature of CPT resonance is embedded in the photoelectric signal. The contrast defined as the ratio of the CPT signal amplitude to the total light background on the CPT resonance is a quantity which reflects the quality of resonance signal (see Fig. 1). At three different cell temperatures, we investigate the relationship between contrast and N_2 pressure. Figure 4 shows the experimental results. From this figure, it is seen that the contrast does not change monotonically with N_2 pressure, and there appears maximum at high temperature. The higher the cell temperature is, the faster the contrast changes around the maximum, and the higher the pressure at which the contrast reaches maximum will be.

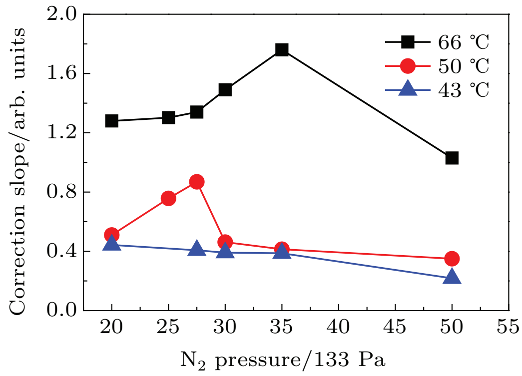

Fig. 5. (color online) Plots of the CPT signal correction slope versus N_2 pressure at laser intensity of 8.18 mW/cm^2.

For application in atomic clocks, the CPT signal is commonly converted into differential forms as error signal in order to realize negative feedback for microwave frequency stabilization. The correction slope, the differential signal slope at the frequency of CPT resonance, is directly concerned. Larger correction slope leads to more stable frequency. Figure 5 shows our experimentally measured results on the slope. Similar to the contrast in Fig. 4, at high temperature there appears the maximum although the location is different.

Except for preventing collision and repopulation collision, fluorescence quenching is another contribution of buffer gas to the concerned configuration for CPT resonance. During CPT state preparation, certain atoms will be pumped into the excited state, and their spontaneous radiation washes out certain prepared CPT states. An extra function of buffer gas is to quench the fluorescence by depopulating the excited atoms through inelastic collision. For rubidium, the quenching cross section of N_2 is three orders larger than those of the commonly used inert gases,[21] which makes it an excellent buffer gas for rubidium-based CPT resonance.

Basically, the CPT resonance is realized at high temperature in practical applications. Our experiment reveals that the main behaviors of ^{85}Rb CPT resonance do not change with N_2 pressure monotonically. At higher temperature, the behaviors depend on pressure more sensitively. For the sake of contrast, the maximum exists at the right N_2 pressure, and a similar maximum appears for the correction slope as well. Therefore, it is important to choose a proper pressure to make the CPT resonance close to the best working point.

4. Conclusions

In order to exploit potential applications of CPT resonance with ^{85}Rb as working atoms and N_2 as buffer gas, we experimentally study the dependence of the CPT resonance on the buffer gas pressure. Our experimental results reveal that at higher temperature, ^{85}Rb-based CPT resonance depends on the buffer gas N_2 pressure more sensitively. At high vapor cell temperature, the quality of CPT resonance does not change monotonically with the buffer gas pressure. In practical applications, the cell temperature is usually high, so properly arranging the working point close to the maximum is important.

Both ^{85}Rb and N_2 are low-cost samples which make the associated CPT resonance more competitive in applications. For the CPT resonance generated with rubidium, the fluorescence quenching effect of N_2 is much stronger than other buffer gases, which makes N_2 the ideal buffer gas candidate for ^{85}Rb-generated CPT resonance. Our experimental results provide valuable data for the applications based on CPT resonance with ^{85}Rb as the working atoms and N_2 as buffer gas.

References

[1] Vanier J, Godone A and Levi F 1998 *Phys. Rev. A* **58** 2345
[2] Knappe S, Shah V, Schwindt P D D, Hollberg L, Kitching J, Liew L A and Moreland J 2004 *Appl. Phys. Lett.* **85** 1460
[3] Lutwak R, Vlitas P, Varghes M, Mescher M, Serkland D K and Peake G M 2005 *Proc. IEEE Int. Freq. Control Symp.* p. 752
[4] Scully M O and Fleischhauer M 1992 *Phys. Rev. Lett.* **69** 1360
[5] Nagel A, Graf L, Naumov A, Mariotti E, Biancalana V, Meschedeand D and Wynands R 1998 *Euro. Phys. Lett.* **44** 31
[6] Schwindt P D D, Knappe S, Shah V, Hollberg L, Kitching J, Liew L and Moreland J 2004 *Appl. Phys. Lett.* **85** 6409
[7] Su J, Deng K, Guo D Z, Wang Z, Chen J, Zhang G M and Chen X Z 2010 *Chin. Phys. B* **19** 110701
[8] Zhou Z C, Wei R, Shi C Y, Li T and Wang Y Z 2011 *Chin. Phys. B* **20** 034206
[9] Huang K K, Li N and Lu X H 2012 *Chin. Phys. Lett.* **29** 100701
[10] Zhang J H, Liu Q, Zeng X J, Li J X and Sun W M 2012 *Chin. Phys. Lett.* **29** 068501
[11] Zhang Y, Qu S and Gu S 2012 *Opt. Express* **20** 6400
[12] Yun P, Zhang Y, Liu G, Deng W, You L and Gu S 2012 *Euro. Phys. Lett.* **97** 63004
[13] Yang J, Liu G B and Gu S 2012 *Acta Phys. Sin.* **61** 043202 (in Chinese)
[14] Liu G B, Du R C, Liu C Y and Gu S H 2008 *Chin. Phys. Lett.* **25** 472
[15] Liu G and Gu S H 2010 *J. Phys. B* **43** 035004
[16] Goka S, Okura T, Moroyama M and Watanabe Y 2008 *Proc. IEEE Int. Freq. Control Symp.* p. 103
[17] Liu L, Guo T, Deng K, Liu X Y, Chen X Z and Wang Z 2007 *Chin. Phys. Lett.* **24** 1883
[18] Seltzer S J, Rampulla D M, Rivillon-Amy S, Chabal Y J, Bernasek S L and Romalis M V 2008 *J. Appl. Phys.* **104** 103116
[19] Allred J C, Lyman R N, Kornack T W and Romalis M V 2002 *Phys. Rev. Lett.* **89** 130801
[20] Alcock C B, Itkin V P and Horrigan M K 1984 *Can. Metall. Q* **23** 309
[21] Vanier J and Audoin C 1989 *The Quantum Physics of Atomic Frequency Standards* (Bristol: Adam Hilger)
[22] Vanier J 2005 *Appl. Phys. B* **81** 421
[23] Micalizio S, Godone A, Levi F and Vanier J 2006 *Phys. Rev. A* **73** 033414
[24] Bender P L 1963 *Phys. Rev.* **132** 2154
[25] Bean B L and Lambert R H 1975 *Phys. Rev. A* **13** 492
[26] Vanier J, Simard J F and Boulanger J S 1974 *Phys. Rev. A* **9** 1031
[27] Vanier J, Godone A and Levi F 1998 *Phys. Rev. A* **58** 2345
[28] Gu S and Behr J 2003 *Phys. Rev. A* **68** 015804
[29] Knappe S, Hollberg L and Kitching J 2004 *Opt. Lett.* **29** 388