Coherent population trapping in small- and chip-scale ^{87}Rb vapor cells with buffer gas

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Received 22 September 2015

Published 18 March 2016

The characteristics of coherent population trapping (CPT) signal were investigated in small-size glass vapor cells containing ^{87}Rb and Ne buffer gas with narrow line-width laser pumping on D₂ line. The parameters of CPT signals were measured using small-size vapor cells with Ne buffer gas pressure in the range of 200–400 Torr, cell temperature in the range of 65–120 °C and the values of laser pumping power of 30–400 $\mu\text{W}/\text{cm}^2$. Optimal conditions, under which the minimal value of short-term instability of resonance line is achieved, were obtained in experiments. Orientation frequency shifts of CPT resonance using glass ^{87}Rb vapor cells containing buffer gas and anti-relaxation coating were compared. CPT signals using vapor cells based on integrated technologies containing ^{87}Rb in atmosphere of Ne were also investigated. The CPT signals with typical line widths of 2–3 kHz and signal-to-noise ratio of 1500 in 1 Hz bandwidth are observed, which allows one to provide relative frequency instability of 10^{-11} at 100 s.

Keywords: Optical pumping; coherent population trapping; vapor cells; resonance signal.

PACS numbers: 42.50.Gy, 06.30.Ft

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1. Introduction

The development of modern methods of resonance signals inducing in optically oriented alkali atoms, such as the effect of coherent population trapping (CPT), and the progress in the establishment of coherent light sources with high stability have made possible the creation of a new generation of miniature quantum devices with optical pumping.¹ Such devices include miniature M_x magnetometers² with sensitivity of 5 pT/Hz^{1/2} and small-size quantum frequency standards based on alkali vapor cells (⁸⁷Rb, ¹³³Cs) with physical package volume less than 20 cm³ and relative frequency instability at the level of 10^{-11} s^{-1/2}.³⁻⁵ Metrological characteristics of such devices are largely determined by the choice of the working alkali atoms, by the technology and the fabrication quality of the working vapor cell and by the parameters of the pumping source.

A necessary condition for the development of structure of miniature quantum devices with optical pumping is the use of relatively high pressures of inert gas (up to several atmospheres), injected into alkali vapor cells with the aim of reducing the relaxation effects in the working medium.⁶ This inevitably causes the problem of the shift and broadening of resonance absorption line, which requires careful selection and adjustment of all elements of the physical package of a quantum device, which allows one to implement the minimum measuring error.

2. Experimental Setup

In this work we investigated characteristics of CPT signal in vapor of ⁸⁷Rb isotope, which possesses simple structure of energetic levels in comparison with ¹³³Cs atoms. The use of neon (Ne) as a buffer gas is allowed, according to preliminary calculations, to ensure relative frequency instability of miniature atomic clocks of 10^{-11} – 10^{-12} s^{-1/2}. The research was carried out on the universal experimental setup with laser pumping source, which made it possible to record CPT signals and signals of double radio-optical resonance. In the setup we provided for the heating of the working vapor cells in the range of temperatures of 20–120 °C and the modulation of the pumping source frequency up to 10 GHz. The functionality of the experimental setup also allow the wide range of investigations, related to the so-called light shifts of the resonance line in quantum device, which are one of the destabilizing factors of frequency standards.⁷⁻⁹

We used the external cavity laser as a pumping source, which allowed to provide high stability of irradiation characteristics (spectral width less than 1 MHz) and high intensity (30–150 mW) in a wide range of adjustment. Photoreceiver served as a silicon photodiode with working area size 1×1 mm and responsivity 0.1 A/W.^{10,11} We used the photodiode in short circuit mode, which excluded the influence of the dark current on the output signal when the bandwidth of registration is 0–20 kHz. The laser was tuned to the D₂ line of rubidium atoms (the wavelength is $\lambda=780$ nm) with adjustable polarization of the pumping radiation.

Fig. 1. Experimental setup: L — laser, EOM — electro-optical modulator, MWFG — microwave generator, CL — collimator, P — polaroids, Rb Cell — cell with rubidium, PhR — photoreceiver, A — amplifier, OSc — oscilloscope, T — thermostat, TCU — thermostat control unit, Ht — heater, Rt — thermistor, MS — magnetic shield, LCU — laser control unit, LFMG — low-frequency modulation generator, λ -CPT — a simplified structure of energy levels in rubidium in the case the CPT signal is produced according to the λ -scheme.

The scheme of experimental setup is presented in Fig. 1. A laser beam (L) was fed to an electro-optical phase modulator (EOM) modulated by a sinusoidal signal from a microwave generator (MWFG). At the EOM output, the first order spectral -1 and $+1$ components separated by twice the frequency of the modulating microwave signal appeared. The carrier component "0" was suppressed by 70% as compared with its intensity at the EOM input. Then the light passed through a collimator (CL) and polaroids (P) ($\lambda/2$ and $\lambda/4$), was partially absorbed in the cell (Rb Cell) and was detected by a photoreceiver (PhR). After that the signal amplified by an amplifier (A) was fed to the oscilloscope (OSc) input.

When the difference between the frequencies of the first order spectral -1 and $+1$ components was equal to the resonant frequency of hyperfine transition of the ground state in ^{87}Rb atoms (6.834 GHz), so-called "dark" resonance appeared and the absorption of the laser light inside the vapor cell reduced. To select 0-0 magnetically independent transition, the cell was put into a uniform magnetic field B_0 (~ 100 mG), which was parallel to the laser beam.

The cell temperature was stabilized with an accuracy of ± 0.1 °C by a thermostat (T) that included a heating element (Ht) and a thermistor (Rt) that provided measurements of the cell temperature. The thermostat was controlled by a control unit (TCU). A magnetic shield (MS) screened the cell from external magnetic fields, the internal magnetic field B_0 was produced by a built-in coil. A low-frequency modulation generator (LFMG) provided the modulation of the resonance conditions with frequency of 23 Hz for observation of CPT signals. A laser control unit (LCU) was used to stabilize laser current and temperature.

3. Coherent Population Trapping in Small-Size Rubidium Cells

In experiments we obtained the optimal values of the buffer gas pressure in the alkali vapor cell, the temperature of the cell and the intensity of the laser pumping radiation corresponding to maximal quality factor of CPT signal. We investigated the line shape of the resonance signals using small-size glass cylindrical cells with size of $\varnothing 3 \times 3$ mm, manufactured according to the conventional technology. The cells contained ^{87}Rb atoms with different pressures of buffer gas Ne (200, 300 and 400 Torr). The Fig. 2 shows the experimentally obtained dependence of the CPT signal from f — detuning the double modulation frequency of laser radiation relative the frequency of hyperfine transition, for the cells with temperature of $T \sim 80^\circ\text{C}$, power density of circularly polarized laser radiation of $400 \mu\text{W}/\text{cm}^2$ and signal registration bandwidth of 10 kHz. As can be seen from Fig. 2, increasing the buffer gas pressure more than 300 Torr leads to a decrease in the amplitude of the resonance signal. This, apparently, is connected with increase of collision frequency between alkali atoms and buffer gas atoms, which leads to depolarization effect.¹²

The parameters of CPT signals for the vapor cells containing buffer gas Ne with pressure values of 200, 300 and 400 Torr are presented in Table 1, where P_{Ne} — neon pressure, F — frequency of hyperfine transition, Δf — line width of the CPT resonance, $(S/N)_{1\text{Hz}}$ — the signal-to-noise ratio in the 1 Hz band, Q — the

Fig. 2. CPT signals at different neon pressures in the cell (1 — $P_{\text{Ne}}=200$ Torr, 2 — $P_{\text{Ne}}=300$ Torr, 3 — $P_{\text{Ne}}=400$ Torr).

Table 1. Parameters of CPT signal in dependence on pressure of Ne in the cell.

P_{Ne} , Torr	F , GHz	Δf , kHz	$(S/N)_{1\text{Hz}}$	Q	σ , $\text{s}^{-1/2}$
200	6.834733	5.90	3900	1.16×10^6	2.21×10^{-10}
300	6.834764	3.00	3800	2.28×10^6	1.16×10^{-10}
400	6.834780	2.89	2900	2.36×10^6	1.46×10^{-10}

quality factor of the resonance equal to the ratio between the transition frequency and resonance line width and σ is the short-term instability of CPT signal. The minimal value of short-term instability was $\sigma=1.16\times10^{-10} \text{ s}^{-1/2}$. This value was observed using the cell with Ne pressure of 300 Torr with signal-to-noise ratio of 38 in registration bandwidth 10 kHz and with resonance line width of 3 kHz. The estimation of the short-term instability of resonance lines was performed according to the equation (1)¹²

$$\sigma = \left(\left(\frac{S}{N} \right)_{1\text{Hz}} \times Q \right)^{-1}. \quad (1)$$

The increase in short-term instability at a pressure of neon of $P_{\text{Ne}}=400$ Torr is caused by a decrease in the amplitude of the test signal, which reduces the signal-to-noise ratio. At the same time the large magnitude of instability when $P_{\text{Ne}}=200$ Torr is due to the line width of the CPT resonance (see Table 1).

In accordance with Fig. 2 the optimal cell with buffer gas by a factor of the line width is the cell with the pressure $P_{\text{Ne}}=400$ Torr. Presented on Fig. 3 (left) waveforms of the CPT signals at the intensity of the pumping radiation $180 \mu\text{W}/\text{cm}^2$ and the cell temperature $T=65\text{--}85^\circ\text{C}$ show a slight increase in line width with increasing temperature. At the same time the short-term frequency instability of the CPT signal (Fig. 3 (right)), corresponding to the so-called flicker limit of the quantum frequency standard, $\sigma=4.69\times10^{-11} \text{ s}^{-1/2}$ is achieved at the temperature of the working cell $T\sim 75^\circ\text{C}$.

From experimental data it follows that the intensity of the CPT signal is directly proportional to the intensity of pumping radiation. This indicates the absence of saturation effects, while the line width decreases in proportion to the pumping intensity, reaching values of the order of 1 kHz when the laser power density is

Fig. 3. (left) — CPT signals at different temperatures of the cell with neon pressure $P_{\text{Ne}}=400$ Torr (1 — $T=68.4^\circ\text{C}$, 2 — $T=76.3^\circ\text{C}$, 3 — $T=81.6^\circ\text{C}$, 4 — $T=84.2^\circ\text{C}$). (right) — The dependence of a short-term instability estimation on the cell temperature at neon pressure in the cell $P_{\text{Ne}}=400$ Torr.

about $30 \mu\text{W}/\text{cm}^2$. When the pumping power density is $60 \mu\text{W}/\text{cm}^2$, the optimal value of the parameter $\sigma=4.49 \times 10^{-11} \text{ s}^{-1/2}$ is achieved.

The peculiarity of the investigated small-size cells with a high pressure of a buffer gas is the broadening of the absorption line that overlaps the splitting of the hyperfine structure of the ground state. Thus the spectral response of the atoms of the working substance on the effect of laser radiation (so-called light shift) is several orders of magnitude less than that observed in small-size cells with anti-relaxation coating, which amounted to the value in the range of 1–10 Hz at the power density of the pumping $100 \mu\text{W}/\text{cm}^2$. This value corresponds to relative frequency shift $\Delta f/F=10^{-9}-10^{-10}$. The use of circularly polarized radiation of the laser source is equivalent to the application of a magnetic field, which direction depends on the sign of the polarization of the pumping radiation. According to Ref. 13 we can estimate the shift of 0-0 hyperfine transition frequency in a rubidium cell with a pressure of neon of 300 Torr during a change of sign of the polarization of the light at 0.1 Hz with pumping power density of $100 \mu\text{W}/\text{cm}^2$. Thus, the variation of the angle θ between the magnetic field direction and the pump beam in 1° corresponds to a relative frequency shift of the 0-0 transition at the level of 5×10^{-12} , which in the order of magnitude coincides with the estimation of the orientation frequency shift, that was performed in Ref. 9. Such compliance was the reason for the experimental evaluation of orientation shift of CPT frequency in small (1 cm^3) rubidium cells coated. Orientation frequency shift is substantially dependent on the adjustment of the laser frequency on the line of the atomic transition, and ranged between $10^{-11}-10^{-13}$ per degree of variation of the angle θ in terms of the power of the laser source to a value of $100 \mu\text{W}/\text{cm}^2$.

4. Investigation of Microfabricated Cells

As it was shown the cell quality strongly depends on the amount of alkali metal, the buffer gas pressure and composition, and the presence of impurities in the cell and directly affects the stability and reproducibility of the characteristics of frequency standards and atomic magnetometers. The most appropriate technology that can ensure a high quality of cells for such devices is the micro electro-mechanical systems (MEMS) manufacturing technology. It combines the advantages offered by the techniques of microelectronic component fabrication and manufacturing and assembling miniature mechanical systems.¹⁴

For the studies, cells with a universal construction (Fig. 4) were fabricated.⁵ The additional cavity 2 (see Fig. 4) was necessitated by the use of the method of recovery of an alkali metal from the rubidium dichromate salt including interaction of a material with an activating laser radiation.¹⁵ Channels 3 (Fig. 4) provided, due to a small cross-section, a transfer of rubidium atoms into the working cavity without byproducts formed during recovery of alkali vapors.

Fig. 4. Microfabricated cell: 1, 2 – working and additional cavity, respectively, 3 – connecting channels, 4, 5 – silicon and glass plates, respectively.

The CPT signals with a typical line width of 2–3 kHz and a signal-to-noise ratio of 1500 in the 1 Hz bandwidth were observed in the experiments using chip-scale microfabricated rubidium cell, described above, with a working cavity volume of 1.2 mm^3 manufactured using the MEMS technique. By substituting the resonance line parameters into expression (1), we obtain the estimate of the short-term frequency instability $\sigma = 1.4 \times 10^{-10} \text{ s}^{-1/2}$, which allows one to provide relative instability of 10^{-11} at 100 s.

5. Conclusion

The result of this work can be used in the development of miniature frequency standards and quantum magnetometers with laser pumping. The studies of CPT signals using small-size vapor cells with linear dimensions of the cavity on the order of 1 mm allowed us to obtain optimal parameters of the pumping intensity, buffer gas pressure and the cell temperature. The results showed that by adjusting the parameters of the physical package of a quantum device the values of frequency instability can be reached at the level of $\sigma = 5 \times 10^{-11} \text{ s}^{-1/2}$.

The results obtained in studies of parameters of resonance CPT signals from microfabricated cell manufactured using the MEMS technique suggest that this technique is efficient for the development of chip-scale quantum devices with laser pumping and relative frequency instability of $\sigma = 1.4 \times 10^{-10} \text{ s}^{-1/2}$.

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