Investigation of coherent population trapping signals in $^{87}$Rb cells with buffer gas

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Abstract. Characteristics of CPT (coherent population trapping) signal are investigated in small-size glass vapor cells containing $^{87}$Rb and Ne buffer gas with narrowlinewidth laser pumping on D$_2$ line. Parameters of CPT absorption signals are measured using small-size vapor cells with Ne buffer gas pressure in range of 200–400 Torr, cell temperature in range of 65–120 °C and values of laser pumping power of 30–400 µW/cm$^2$. Optimum conditions, under which the minimal value of short-term instability of resonance line is achieved, are obtained in experiments. CPT signals using vapor cells based on integrated technologies containing $^{87}$Rb in atmosphere of Ne are also investigated. The CPT signals with typical linewidths 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.

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 Mx magnetometers [2] with sensitivity of 5 pT/Hz$^{1/2}$ and small-size quantum frequency standards based on alkali vapor cells ($^{87}$Rb, $^{133}$Cs) with physical package volume less than 20 cm$^3$ 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 $^{87}$Rb isotope, which possesses simple structure of energetic levels in comparison with $^{133}$Cs 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$^2$ 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 D$_2$ line of rubidium atoms (the wavelength is $\lambda=780$ nm) with adjustable polarization of the pumping radiation.

The scheme of experimental setup is presented on figure 1. A laser beam (L) was fed to an electro-optical phase modulator (EOM) modulated by a sinewave 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.

![Experimental setup diagram](image)

**Figure 1.** Experimental setup: L – laser, EOM – electrooptical modulator, MWFG – microwave generator, CL – collimator, P – polaroids, Rb Cell – cell with rubidium, PhR – photoreceiver, A – amplier, OSc – oscilloscope, T – thermostat, TCU – thermostat control unit, Ht – heater, Rt – thermistor, MS – magnetic shield, LCU – laser control unit, LFMG – low-frequency modulation generator, $\lambda$-CPT – a simplified structure of energy levels in rubidium in the case the CPT signal is produced according to the $\lambda$-scheme.
Then the light passed through a collimator (CL) and polaroids (P) \((\lambda/2 \text{ and } \lambda/4)\), 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 \(^{87}\text{Rb}\) 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 \(\pm0.1\) °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 \(3\times3\) mm, manufactured according to the conventional technology. The cells contained \(^{87}\text{Rb}\) atoms with different pressures of buffer gas Ne (200, 300 and 400 Torr). Figure 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 \(T\sim80\) °C, power density of circularly polarized laser radiation of 400 \(\mu\text{W/cm}^2\) and signal registration bandwidth of 10 kHz. As can be seen from figure 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]

![Figure 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).](image-url)
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 \( P_{\text{Ne}} \) – neon pressure, \( F \) – frequency of hyperfine transition, \( \Delta f \) – linewidth of the CPT resonance, \( (S/N)_{1\text{Hz}} \) – the signal-to-noise ratio in the 1 Hz band, \( Q \) – the quality factor of the resonance equal to the ratio between the transition frequency and resonance linewidth and \( \sigma \) is the short-term instability of CPT signal. The minimal value of short-term instability was \( \sigma = 1.16 \times 10^{-6} \text{s}^{-1/2} \). 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 linewidth of 3 kHz. The estimation of the short-term instability of resonance lines was performed according to the equation (1) [12].

\[
\sigma = \left[ \frac{S}{N} \right]_{1\text{Hz}} \times Q^{-1}
\]

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 amount of instability when \( P_{\text{Ne}} = 200 \) Torr is due to the linewidth of the CPT resonance (see table 1).

In accordance with figure 2 the optimal cell with buffer gas by a factor of the linewidth is the cell with the pressure \( P_{\text{Ne}} = 400 \) Torr. Waveforms of the CPT signals at the intensity of the pumping radiation 180 \( \mu \text{W/cm}^2 \) and the cell temperature \( T = 65 \text{–} 85 \) °C, presented in figure 3, show a slight increase in linewidth with increasing temperature. At the same time the short-term frequency instability of the CPT signal (figure 4), corresponding to the so-called flicker limit of the quantum frequency standard, \( \sigma = 4.69 \times 10^{-11} \text{s}^{-1/2} \) is achieved at the temperature of the working cell \( T \approx 75 \) °C.

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

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

**Figure 3.** CPT signals at different temperatures of the cell with neon pressure \( P_{\text{Ne}}=400 \) Torr (1 – \( T=68.4 \) °C, 2 – \( T=76.3 \) °C, 3 – \( T=81.6 \) °C, 4 – \( T=84.2 \) °C).

**Figure 4.** The dependence of a short-term instability estimation on the cell temperature at neon pressure in the cell \( P_{\text{Ne}}=400 \) Torr.
From experimental data it follows that the intensity of the CPT signal is directly proportional to the intensity of pumping radiation, indicating the absence of saturation effects, while the linewidth decreases in proportion to the pumping intensity, reaching values of the order of 1 kHz when the laser power density is 30 μW/cm². When the pumping power density is 60 μW/cm², the optimal value of the parameter $\sigma = 4.49 \times 10^{-11} \text{s}^{-1/2}$ is achieved.

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 [13].

For the studies, cells with a universal construction (figure 5) were fabricated [5]. The additional cavity 2 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 [14]. Channels 3 provided, due to a small cross-section, a transfer of rubidium atoms into the working cavity without byproducts formed during recovery of alkali vapors.

The CPT signals with a typical linewidth 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 mm³ manufactured using the MEMS technique. By substituting the resonance signal 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. Summary
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 frequency instability of $\sigma = 1.4 \times 10^{-10} \text{s}^{-1/2}$. 

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