Light shifts in the rubidium CPT atomic clock with laser current modulation at 3.4 and 6.8 GHz

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Abstract. In the paper presents results of an experimental comparison of the CPT parameters of the resonance at the D1 line in $^{87}$Rb when the laser current is modulated at frequencies 3.4 GHz and 6.8 GHz. Resonances are investigated for slope to noise ratio (Q-factor) and shifts from the microwave power. The reproducibility of the parameters of VCSEL lasers required to obtain long-term stability of an atomic clock is considered. The obtained CPT instabilities of the atomic clock for 1 second were $1.2 \times 10^{-11}$ for the case of 3.4 GHz and $4 \times 10^{-12}$ for 6.8 GHz.

1. Introduction.
The coherent population trapping (CPT) resonance in alkali atoms is widely used to build miniature atomic clocks [1, 2]. The CPT technology can significantly reduce the size, power and cost of atomic clocks [3-5]. Many CPT clocks use a vertical-cavity surface-emitting laser (VCSEL) [6] whose current is modulated by a generator with a frequency equal to half of the hyperfine splitting of the ground atomic state. Due to this modulation, the single-frequency laser mode acquires additional spectral components - sidebands. Usually two sidebands of the first order of the laser are used to excite CPT resonance in a two-photon $\lambda$ scheme. Since the modulation frequency is half the hyperfine splitting of the ground-state atom, which is 6.8 GHz on the D1 line in $^{87}$Rb, this is the case of modulation at 3.4 GHz. Another type of modulation considered here is the modulation of the laser current with a frequency equal to the hyperfine splitting of an atom in the ground state of 6.8 GHz. [7, 8]. With such modulation, the carrier and one of the first order sidebands are used to excite the CPT resonance according to the two-photon $\lambda$ scheme. The CPT resonance can also be obtained at other laser current modulation frequencies that are multiples of the hyperfine splitting of the ground state of the atoms, but with increasing multiplicity, the spectrum of the side bands broadens, and the amplitudes of the two components participating in the two-photon $\lambda$-scheme become smaller. The rest of spectrum is produce background for the resonance by reducing contrast and increasing the optical noise.

The short-term stability of an atomic clock is inversely proportional to the resonance width and directly proportional to the signal-to-noise ratio determined by the resonance contrast and the shot noise of the radiation. Long term stability is determined by various frequency offsets. The dependence of the frequency shifts is investigated on operating parameters such as the light intensity, the value of the microwave power modulating the laser current, the optical detuning from the optical transition frequency, the temperature of the absorbing cell, the pressure of the buffer gas in the cell, and the external magnetic field.
This paper presents the results of studying the parameters of the CPT resonance in $^{87}$Rb on the D1 line and the light shift for the case of modulation of the laser current at frequencies of 3.4 GHz and 6.8 GHz.

2. Experimental setup

The setup (figure 1) includes a VCSEL operating at a wavelength of 795 nm, corresponding to the D1 line of $^{87}$Rb. The laser is equipped with a precision current source and a temperature stabilization system. The laser output is linearly polarized and passes through the quarter-wave phase plate to obtain circular polarization. A gradient ND filter is used to modulate the radiation power level. It is slightly tilted relative to the position orthogonal to the beam to prevent reflections back into the laser. After that, the radiation is passed through an absorbing cell with rubidium vapor and a buffer gas. To observe absorption in alkali metal atoms, the cell is uniformly heated to more than 50 °C. Due to the design features, the cell windows are at a lower temperature. At the same time, metal condensation is observed on the windows. To solve this problem, the cell temperature $T_c$ is maintained at 5 °C higher than the temperature of the $T_f$ branch containing the metallic rubidium.

Helmholtz coils are located on the cell body to create a uniform magnetic field directed along the wave vectors of the waves. This field splits the energy levels of the ground state and allows one to observe the CPT resonance associated only with magnetic sublevels with quantum numbers $m_F = 0$, for which there is no linear Zeeman effect. At the same time, these levels undergo a quadratic shift in the magnetic field, which leads to a corresponding shift of the CPT resonance (frequency of the clock “0–0” transition):

$$\Delta \nu = K_0 B^2,$$

(1)

where $B$ is the magnetic induction (in Gs). Based on the Breit-Rabi formula [9], it can be shown that for $^{87}$Rb the proportionality coefficient is $K_0 = 575.14$ Hz/Gs$^2$. The magnitude of the magnetic field in our case was 100 - 150 mG.
To obtain resonant optical frequencies for the $\lambda$ scheme of two photon interaction $\nu_1$ and $\nu_2$ in the laser emission spectrum, its current was modulated at frequencies of 3.417 GHz and 6.834 GHz. For 3.4 GHz modulation, we used a proprietary microwave generator used as part of a miniature atomic clock, and for 6.8 GHz we used a Rognhe & Schwarz SMA-100B RF and microwave signal generator. The frequencies $\nu_1$ and $\nu_2$ are side frequencies of orders $\pm 1$ of the resulting frequency modulated (FM) laser radiation. In this case, the oscillator frequency is synthesized from a frequency of 10 MHz from a temperature compensated crystal oscillator (TCXO).

An automatic control system, operating at a laser current modulation frequency of 15 kHz, stabilizes the optical frequency of lasing along the D1 absorption line of $^{87}$Rb. To obtain an error signal, the first harmonic of the modulation of the optical power of the beam passing through the rubidium cell is synchronously detected. The operating frequency of the probe modulation (15 kHz) was chosen on the basis that at this frequency, both the laser and the electronic elements usually do not have excessive flicker noise. You can control the laser generation frequency by changing its current or temperature. Current changes in speed are many times higher than the temperature method, but with a change in current, the output power of the laser, impedance, and modulation characteristics change to a much greater extent. Taking into account this feature, the processing of the error signal of the automatic control system is carried out by adjusting the laser temperature, and the test modulation through the laser current. Also, this approach compensates for the error of inaccuracy in measuring the temperature of the diode by the thermal sensor, associated with their different location in space.

To stabilize the frequency of the microwave generator, a stabilization method is used, which is similar to the Pound-Drever-Hall method used to stabilize the frequency of lasers in the optical range [10]. In this method, the modulation frequency significantly exceeds the resonance width. In our case, we use an automatic control system with a modulation frequency of $\approx 9$ kHz with a full width at half maximum (FWHM) of the observed CPT resonance equal to 680 Hz. This method has a number of advantages, namely, it allows you to realize the maximum possible feedback speed, to select a high operating frequency to improve the signal-to-noise ratio.

The absorbing cell is made of quartz glass, resistant to alkali metals and having low gas permeability (for example, grade C51-1). The glass cell contains the pure isotope $^{87}$Rb, a buffer inert gas ($\approx 100$ Torr). In the absence of a buffer gas, the time of coherent interaction of rubidium atoms with the laser field is much shorter and equal to the average time of flight of atoms through the beam, which leads to a significant broadening of CPT resonances.

3. Resonances with modulation of the laser current at 3.4 GHz frequency.

Sensitivity to the following parameters is the main source of long-term instability in manual CPT watches:
- intensity of optical radiation
- microwave power modulation
- collisional shift from buffer gases when the cell temperature changes
- shift from the change in the concentration of rubidium atoms with a change in the cell temperature
- shift from the magnetic field in the cell.

Changing the modulation frequency from 3.4 to 6.8 GHz affects only the first two shifts, the rest of the dependences will behave regardless of the modulation method [11].

The created experimental setup made it possible to observe CPT resonances, measure their parameters and, directly from the signal in the microwave frequency stabilization system, determine the frequency discriminator slope, both for the case of laser current modulation at a frequency of 3.4 GHz and at a frequency of 6.8 GHz. A typical record of the CPT resonance for the case of modulation at a frequency of 6.8 GHz is shown in figure 2, and the error signal in the microwave frequency stabilization system in figure 3.
To study the field frequency shifts as a function of the microwave power modulating the laser current, the microwave frequency was stabilized by the CPT resonance frequency and the frequency of the atomic standard was measured relative to the hydrogen standard frequency. For this, the 10 MHz output frequencies of the atomic standard based on $^{87}$Rb and the Ch1-1007 hydrogen frequency and time standard were fed to the VCH-323 phase comparator - analyzer. The microwave power was changed stepwise at each step, and the frequency of the atomic standard was measured based on the CPT resonance in $^{87}$Rb on the D1 line. The figure 4 shows the measurement results for the case of modulation of the laser current at a frequency of 3.4 GHz for two VCSEL.

For one of the VCSEL, the dependence has an extremum, which we used earlier [11] to increase the long-term stability of the frequency of the atomic standard. At this point, the first derivative of the frequency shift versus microwave power is zero. But upon further investigation, it was found (figure 4) that such a point was not observed in another VCSEL series. To understand the difference between
lasers, the spectra of lasers were studied using a scannable interferometer with a free dispersion region of ~40 GHz.

![Spectra of lasers](image)

**Figure 5.** Spectra of lasers: a - №64, b - №66, at different levels of microwave modulation.

As shown in figure 5 spectra have sidebands located at intervals equal to the modulation frequency. In a laser for which a minimum was observed in the dependence of the frequency shift of the standard on the microwave power, the spectrum looks much more symmetric.

To find the optimal CPT stabilization parameters, the resonance was investigated by two main parameters: the slope of the frequency discriminator depending on the microwave power and the frequency shift of the atomic standard recalculated to 1% of the change in microwave power are plotted in figure 6 for the case of modulation of the laser current at a frequency of 3.4 GHz. The frequency shift of an atomic standard from a change in microwave power by 1% of the operating value of the microwave power is calculated through the first derivative at any selected operating point multiplied by 0.01 of the power value at this point (figure 6). The optimal point for long-term stability in microwave power is $P = 0.16$ mW, since with a small gap in the discriminator steepness, a zero shift from the microwave is observed, which makes the standard insensitive to such a poorly controlled parameter as the amplitude of the output signal of the microwave oscillator.
4. Resonances with modulation of the laser current at 6.8 GHz frequency.

Investigations were carried out in a similar way for the case of modulation of the VCSEL current at a frequency of 6.8 GHz. To begin with, a scanned interferometer was used to observe the laser spectra for the case of current modulation at a frequency of 6.8 GHz. The distribution of amplitudes in the spectral components is shown in figure 7. The side stripes are almost symmetrical.

![Figure 7. The amplitude of the sidebands of the laser with current modulation at a frequency of 6.8 GHz.](image)

Investigations of CPT resonances and the slope of frequency discriminators were carried out for the case of modulation of the laser current at a frequency of 6.8 GHz and after processing all
measurements, two main parameters are the slope of the frequency discriminator obtained on the basis of the CPT resonance depending on the microwave power and the frequency shift of the atomic standard recalculated to 1% of the change in microwave power plotted on one graph for the case of modulation of the laser current at a frequency of 6.8 GHz and are presented in figure 8. A zero shift depending on the microwave power was not observed for this type of modulation; therefore, the optimal laser operation mode was selected according to the maximum discriminator slope at a microwave power of 2.5 mW.

Figure 8. Measurements for the case of modulation of the laser current at a frequency of 6.8 GHz.

Dependence of the slope of the frequency discriminator on the microwave power. Frequency shift of an atomic standard when the microwave power is changed by 1%.

For the case of modulation of the LWR current at a frequency of 3.4 GHz, measurements were carried out only for the laser current $J = 1.3$ mA. For the case of modulation of the LWR current at a frequency of 6.8 GHz, measurements were performed for three values of the laser current $J = 1.7$ mA, $J = 1.5$ mA, and $J = 1.3$ mA. In addition, the λ scheme for observing the CPT resonance for the case of modulation of the LVD current at a frequency of 6.8 GHz can be constructed in two versions using the low-frequency sideband and the central lasing band of the laser, and the second version using the high-frequency sideband and the central lasing band of the laser. In total, there are six different options.

Further, the field frequency shifts of the standard were investigated for the case of a modulation frequency of 6.8 GHz. The measurement results for all six cases are presented in figure 9.
Figure 9. Field frequency shifts of the standard for the case of a modulation frequency of 6.8 GHz depending on the microwave power for various laser currents. CPT resonance was obtained from different components of the radiation spectrum: LF - carrier + low-frequency sideband, HF - carrier + low-frequency sideband.

It can be seen from the graphs that the shifts from the microwave modulation power are significantly less when stabilized behind the absorption line by a combination of carrier + low-frequency side bands (LF), and when using the HF mode, a point of low sensitivity to changes in the laser current is observed. At the same time, the stability of the current source is a fairly well controlled parameter; therefore, the LF resonance observation mode was chosen as optimal.

After choosing the optimal stabilization parameters, an experiment was set up to measure the Alan function for both cases of modulation (figure 10). It can be seen from the graphs that for 6.8 GHz, a significant improvement was obtained in short times $\sim 3 \cdot 10^{-12} \tau^{-1/2}$. The instability over long periods was due to the relatively high temperature sensitivity of the Rohde & Schwarz SMA-100B microwave generator.
Figure 10. Results of measuring the Alan function for the case of modulation of the laser current at frequencies of 3.4 (red squares) and 6.8 GHz (blue triangles).

5. Conclusion
The studies carried out comparing the parameters of the CPT resonance in 87Rb on the D1 line for the cases of modulation of the laser current at frequencies of 3.4 GHz and 6.8 GHz showed that the slope of the frequency discriminator obtained on the basis of the CPT resonance at the optimal microwave power is the same in both cases. Studies of the field shifts of the frequency standard based on CPT resonances have shown that in the case of modulation of the laser current at a frequency of 6.8 GHz, the field shifts are 2–4 times smaller. The achieved result on short-term stability of $3 \cdot 10^{-12}$ for 1 s showed that this approach is promising for use in miniature atomic clocks.

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