Experimental Investigation of the Dark Pseudoresonance on the $D_1$ Line of the $^{87}\text{Rb}$ Atom Excited by a Linearly Polarized Field

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The measurements of the metrological characteristics (amplitude, width, and shift in the magnetic field) of the dark pseudoresonance, which was proposed by Kazakov et al. [quant-ph/0506167] as the reference resonance for an atomic frequency standard, are reported. It has been shown that the characteristics of the pseudoresonance are worse than those of the unsplit electromagnetically induced transparency resonance for the excitation scheme with the $\text{lin}||\text{lin}$ polarization on the $D_1$ line of the $^{87}\text{Rb}$ atom.

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Since the 1970s, two-photon resonances free of Doppler broadening have been successfully used as a reference for quantum frequency standards [1, 2]. In 1993, the effect of coherent population trapping was proposed to be used to create a microwave frequency standard based exclusively on optical elements without a microwave cavity [3]. In recent years, the possibility of creating an atomic clock based on this effect is actively analyzed [4, 5, 6, 7]. Two copropagating laser fields acting on the allowed electric dipole transitions in the $\Lambda$-configuration create a long-lived superposition of states in hyperfine sublevels of the ground states of the alkali-metal atoms. When the difference between the frequencies varies near the hyperfine splitting frequency $\Delta_{hfs}$, the transmission resonance is observed (named as coherent population trapping resonance or $\Lambda$-resonance). The resonance width in the limit of low intensities is determined by the coherence lifetime in the ground state.

$$\sigma(\tau) = \sqrt{\frac{\eta_{bg}}{\Delta_{hfs}}} \frac{W}{A} \tau^{-1/2}$$ (1)

where $\sigma(\tau)$ is the Allan parameter, $\Delta_{hfs}$ is the standard frequency, and $I_{bg}$ is the background caused by radiation that is not absorbed by the medium. For this reason, the search for schemes for the excitation of the coherent population trapping resonance with high contrast ($>5\%$), minimum width, and light shift is of current interest for an increase in the stability of the clock.

A pushpull pumping scheme that allows the production of a pure coherent state was proposed in [9]. Atoms in such a state do not interact with the field; i.e., the atom-field interaction operator is equal to zero $-\hat{d}\bar{E}|\text{Dark}\rangle = 0$, where $|\text{Dark}\rangle$ is the coherent superposition of the wave functions of the Zeeman sublevels of the ground state. In that work, a contrast of about 30% was experimentally achieved. The pure dark state prepared by means of a standing wave was also demonstrated in [10]. In [11], it is shown that, when the red detuning of the frequency of the pump field is equal to the hyperfine splitting $\Delta_{hfs}$ of the ground state, a contrast of about 20% is reached with almost zero shifts. We note that, although this work does not involve the coherent population trapping effect, it is close to the subject under discussion in its aim: the use of the bichromatic field, and the $\Lambda$-configuration of the involved processes.

It is known that the stability of quantum frequency standards increases with increasing the amplitude $A$ of the resonance and with decreasing its width $W$ ([5], Eq. (8)):

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the coherent population trapping resonance, the pulse scheme of detecting the resonance was studied by the Ramsey method [12]. A unique possibility was pointed out in [13] for forming the pure coherent population trapping resonance (free of trap states) due to the interaction between the bichromatic field with \( \text{lin|lin} \) polarized components and the \( 5P_{1/2} \) state of \(^{87}\text{Rb} \) atoms. In that case, a pure dark state appeared under the action of the linearly polarized bichromatic field under the condition of the spectral resolution of the hyperfine structure of the excited state (Fig.1). The achievement of a contrast of about 50% was reported in that work. It was pointed out that the magnetic field sensitivity (quadratic Zeeman shift) of the proposed resonance should be \( 1/1.33 \) of the shift of the resonance formed due to excitation by the circularly polarized bichromatic field (\( \sigma^+ - \sigma^- \) scheme). In that work, it was also noted that the resonance was split into two resonances in high magnetic fields. This splitting arises because the g factors of two hyperfine sublevels of the ground state are slightly different due to the nuclear-spin contribution.

In [14], it was proposed to use a dip arising due to a splitting of the resonance as the reference for the microwave standard (see Fig.1). The authors of [14] referred to the dip as pseudoresonance, because it appeared due to the splitting of the coherent population trapping resonance in the magnetic field. The estimates made in that work showed the possibility of reaching a frequency stability of \( \frac{10^{-14}}{\sqrt{\tau}} \). Such a high stability would enable one to consider the pseudoresonance as a high-priority and promising tool for creating atomic frequency standards based on the coherent population trapping effect. For this reason, theoretical and experimental investigation of the pseudoresonance, as well as comparison with the unsplit coherent population trapping resonance, seems to be of interest.

In this paper, the experimental results on certain metrological characteristics of the pseudoresonance are reported. It is shown that they are worse than those of the initial (unsplit) coherent population trapping resonance.

Figure 2 shows the layout of the experimental setup that consists of a laser system, a cell filled with \(^{87}\text{Rb} \) vapor, and a detection system. The experiment was conducted with a Pyrex cylindrical cell (40 mm in length and 25 mm in diameter) containing Ne at a pressure of 4 Torr and isotopically pure \(^{87}\text{Rb} \). The cell was placed inside a solenoid, which provided variation in the longitudinal magnetic field. To screen the external laboratory field, the cell was placed inside three cylindrical magnetic screens. The heating of the cell was performed by means of a bifilar nichrome wire coiled around the inner magnetic screen. The cell temperature was equal to 50° C.
to 50°C. The bichromatic resonance field was produced by modulating the current of a “slave” laser whose frequency was matched by the frequency of a single-mode external-cavity injection laser (ECLD, “master”). To this end, the radiation of the latter laser was injected through a isolator into the active region of the driven laser (DL). In this case, the modulation did not disturb the regime of the maser laser (ECLD). The injection current of the driven laser (DL) was modulated at a frequency of $\Delta h/2 = 3.417$ GHz by means of an Agilent E8257D-502 microwave generator, which was connected to the “slave” laser through a Minicircuits ZFBT-6G T bias. Such a procedure ensured the generation of resonant optical fields with a high correlation degree of phase noises. The ratio of the intensities of these fields could be changed by slightly varying the current of the driven laser. The resonant fields carried approximately 50% of the total power of the radiation (2 mW). The ratio of the intensities of the resonant fields was equal to 1.4, and the amplitude of the coherent population trapping resonance was maximal. The remaining power was contained in the carrier and higher order side frequencies. The laser beam in the cell had a diameter of 4 mm. The coherent population trapping resonance was excited by the linearly polarized first-order components, which were tuned to the $F_g = 1 \leftrightarrow F_e = 1$ and $F_g = 2 \leftrightarrow F_e = 1$ transitions. The intensity of the radiation passed through the cell was measured by a photodiode. In order to study the pseudoresonance, the modulation frequency $\Delta h/2$ was linearly scanned in a narrow range ($\sim 150 kH z$) for various magnetic fields. The amplitude and width (Fig.3) of the resonance, as well as its amplitude-to-width ratio and its position (Fig.4), were studied as functions of the magnetic field.

In the absence of the magnetic field, the amplitude of the coherent population trapping resonance is one order of magnitude less than the amplitudes of the resonances observed in the presence of the magnetic field. In the presence of the magnetic field, this resonance is split into three resonances: the magnetically independent central resonance at the transition frequency $\Delta h/2$ and two magnetically dependent resonances. The central resonance is formed by two $\Lambda$ transitions: $\{F_g = 1, m_F = -1 \leftrightarrow F_e = 1, m_F = 0 \}$ and $\{F_g = 2, m_F = -1 \leftrightarrow F_e = 1, m_F = 0 \}$. The main contribution to the magnetically dependent resonances comes from the following $\Lambda$ transitions: $\{F_g = 2, m_F = -1 \leftrightarrow F_e = 1, m_F = 0 \}$ and $\{F_g = 2, m_F = +1 \leftrightarrow F_e = 1, m_F = 0 \}$. Immediately after the appearance of the magnetic field, the amplitude of the central resonance increases and its contrast reaches 40%. The amplitude of the magnetically dependent resonances also increases to 12%. The resonances grow upon the appearance of the magnetic field, because the removal of degeneration destroys dark trap states on the Zeeman sublevels that belong to the same hyperfine level and on which atoms are hidden. To destroy these traps, a magnetic field whose magnitude is higher than the width of the resonance is necessary. In not too strong fields, the width of the resonance is determined by the optical pumping rate for the ground state [13]. A further increase in the magnetic field (to 0.5 G, see Fig.5) results in a new splitting of the central resonance. In this way, the pseudoresonance appears. The amplitude of the pseudoresonance is saturated at a magnetic field exceeding 7.0 G but does not reach the amplitude of the initial coherent population trapping resonance, see Fig.3 (upper panel). The width of

Fig.3: Magnetic-field dependence of the amplitude A (upper panel) and width W (lower panel) of pseudoresonance, where the horizontal straight lines show the respective values of the unsplit coherent population trapping resonance in the presence of a magnetic field of 0.2 G.

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the pseudoresonance becomes less than the width of the initial resonance at a magnetic field of less than 4.0 G, for which the amplitude of the pseudoresonance is very small.

It is seen in Fig.4 that the maximum A/W ratio is reached at a magnetic field of about 3.4G. For this field both the width and amplitude of the pseudoresonance are less than the respective values of the initial resonance. The ratio A/W for the pseudoresonance is worse at any magnetic field. It is worth noting that, for locking of the quartz-oscillator frequency in the atomic clock, resonances with a sharp peak (with a larger slope of the first derivative) are preferable over those with a smooth peak, as in the case of the pseudoresonance.

We point to one more feature of the behavior of the split resonance. Figure 5 shows the shift of two true coherent population trapping resonances (lines a and c) and the pseudoresonance (line b) as the longitudinal field varies. This dependence for the coherent population trapping resonances has the form (see, e.g., [14])

$$\Delta = \Delta_{hfs} + \frac{2g_I\mu_N}{h}H + \frac{3g_I^2\mu_B^2}{8\omega_{hfs}\hbar^2}H^2$$  \hspace{1cm} (2)

where \(\mu_B\) is the Bohr magneton, \(\mu_N\) is the nuclear magneton, and \(g_I\) and \(g_J\) are the nuclear and electron Lande factors, respectively. It is seen that the shift of the coherent population trapping resonances are the sum of the linear and quadratic contributions from both transitions \(m_F = -1 \leftrightarrow m_F = +1\) (left resonance) and \(m_F = +1 \leftrightarrow m_F = -1\) (right resonance) involved in the formation of the reference resonance. For low magnetic fields, the left resonance is shifted from the right resonance (and from the pseudoresonance) according to the linear law. However, as the field increases, the left resonance changes the direction of its shift and begins to move in the same direction as the right resonance, because the quadratic term begins to dominate in Eq. (2).

From experimental line b, the quadratic dependence of the position of the dark resonance on the magnetic field is found with a coefficient of about 0.43 \(\pm 0.04 kH z/G^2\). As was predicted in [13], this coefficient is less than the corresponding coefficient for the standard atomic clock by a factor of 1.33 [10].

In this work, certain metrological characteristics of the dark pseudoresonance have been experimentally studied. The results provide the conclusion that these characteristics are noticeably worse than the respective characteristics of the initial (unsplit) coherent population trapping resonance from which the pseudoresonance appears. Thus, we think that the use of the pseudoresonance as the reference for the atomic clock is not an optimum solution when using the \(lin||lin\) excitation scheme on the \(D_1\) line of the \(^{87}\text{Rb}\) atom. At least more detailed theoretical investigation is required for determining the experimental conditions (cell sizes, buffer gas pressure, etc.) under which the pseudoresonance could be preferable over the unsplit coherent population trapping resonance.

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