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High-contrast dark resonance on the D_2-line of ^{87}Rb in a vapor cell with different directions of the pump-probe waves

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Abstract. We propose a novel method enabling to create a high-contrast dark resonance in the ^{87}Rb vapor D_2-line. The method is based on an optical pumping of atoms into the working states by a two-frequency, linearly-polarized laser radiation propagating perpendicularly to the probe field. This new scheme is compared to the traditional scheme involving the σ^+-polarized probe beam only, and significant improvement of the dark resonance parameters is found. Qualitative considerations are confirmed by numerical calculations.

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Rapid Note

High-precision quantum frequency standards (atomic clocks) become now more and more indispensable in various scientific and engineering applications. A new boost of efforts to create a quantum frequency standard based on the coherent population trapping (CPT) effect has recently begun (of course, CPT standards could be used as secondary frequency standards only, because their stability may hardly reach the level required for primary standards).

The CPT effect of atoms interacting with a resonant electromagnetic field is well-known (see reviews [1,2] and references therein) and widely used in various fields of atomic and laser physics. Efforts to design and build CPT-based atomic clocks were undertaken by several scientific groups [3–8]. The main advantage of quantum frequency standard based on the CPT effect is that the corresponding RF resonance (so-called dark resonance) is excited by all-optical methods. However, practical use of the CPT phenomenon requires thorough optimization of the two-photon resonance parameters (width, amplitude, contrast). Here we propose a new method enabling to improve significantly the characteristics of the signal, due to very efficient accumulation of atomic population in the two working sublevels in a particular optical pumping scheme.

In CPT based clocks, the Zeeman sublevels $|1\rangle = |F = 1,\ m = 0\rangle$ and $|2\rangle = |F = 2,\ m = 0\rangle$ of the two ground-states hyperfine components of an alkali metal atom (^{87}Rb) are the working energy levels. The coherence between these states is created by a two-photon Raman transition induced by a circularly-polarized laser field containing two components with frequencies ω_1 and ω_2

$$\vec{E}(z,t) = \frac{\vec{e}_{+1}}{2}\left(E_1 \exp\left[i(k_1 z - \omega_1 t)\right] + E_2 \exp\left[i(k_2 z - \omega_2 t)\right]\right) + c.c. \quad (1)$$

in the presence of a level-splitting static magnetic field oriented along the z-axis. Here $\vec{e}_{+1} = -(\vec{e}_x + i\vec{e}_y)/\sqrt{2}$ is the unit vector of right-handed circular polarization and $E_{1,2}$ are the amplitudes of corresponding frequency components. Let us introduce the two-photon detuning Ω as

$$\Omega = (\Delta_{hfs} - (\omega_1 - \omega_2))/2, \quad (2)$$

where Δ_{hfs} is the ground state hyperfine splitting. When Ω is scanned across zero, a narrow dip (dark resonance) is observed in the absorption spectrum. The dark resonance width Γ_s is determined by the relaxation rate of the ground state atomic coherence and the laser field parameters [1,2]. However, in the case of circularly-polarized fields there is always a trapping state (so-called "pocket") for an alkaline atom. E.g., for a σ^+-polarized laser radiation this is the sublevel with the maximum projection on the axis z of the total angular momentum. Atoms are accumulated in the pocket and do not contribute anymore

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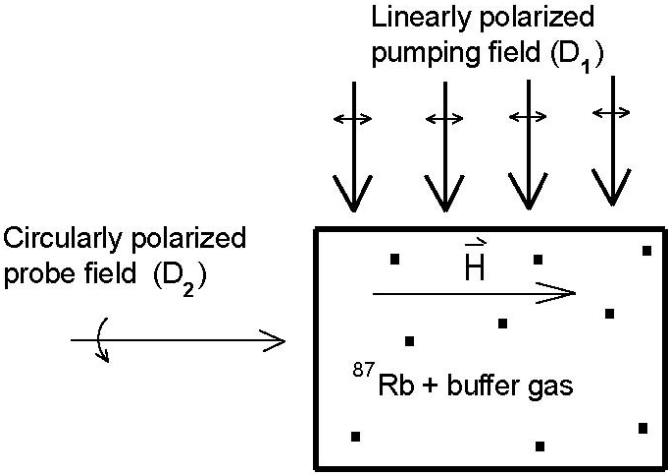

Fig. 1. The proposed Rb gas frequency standard for the novel transversal pumping scheme.

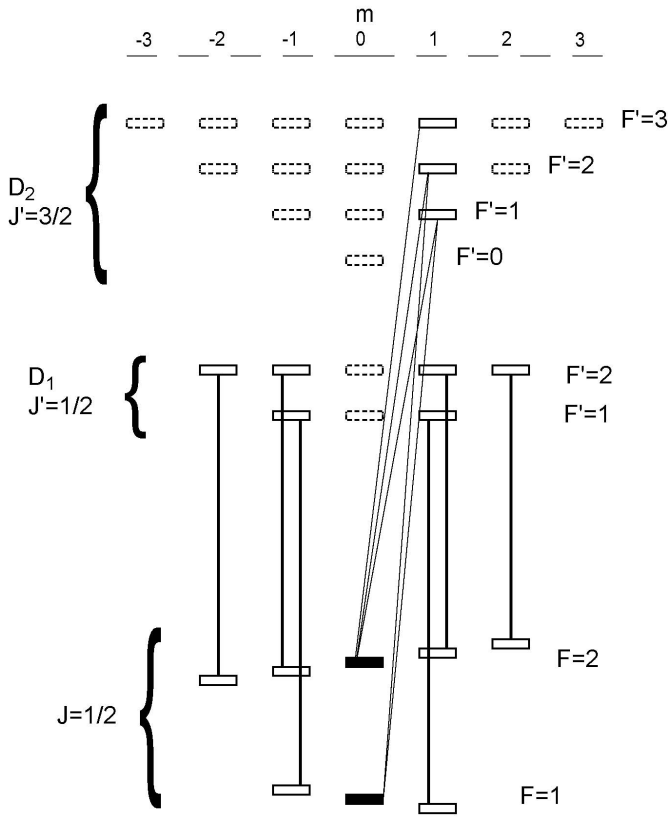

Fig. 2. The scheme of optically-induced transitions between the energy levels of ^{87}Rb. Atoms are accumulated in the two working levels (black rectangles) due to optical pumping via the transitions indicated by bold vertical lines and spontaneous relaxation. The transitions excited by the probe field are shown by thin inclined lines.

to the signal formation on the working transition. It leads to a drastic decrease of the signal amplitude and contrast.

To solve this problem, a scheme involving counter-propagating light waves with orthogonal polarizations has been proposed [5]. In that case, the pocket is absent. However, a significant periodic spatial variation of the resonance amplitude emerges. The period $\pi/(k_1 - k_2)$, where $k_j = 2\pi/\lambda_j$ is the wave number of the laser field of frequency ω_j, is due to the difference of the wavelengths λ_j of the two frequency components of the laser radiation. For example, this period is equal to approximately 2 cm for ^{87}Rb atoms. Therefore spatial averaging over the cell decreases the dark resonance amplitude for the cell length $L \geq \pi/(k_1 - k_2)$ [6]. On the other hand, small cells of the length $L \ll \pi/(k_1 - k_2)$ are characterized by large values of the atomic relaxation at cell walls. To decrease the adverse influence of the wall relaxation, one needs to apply high buffer gas pressure (150 Torr in a cell of 12 mm^3 volume [7]). However, there are also inelastic collisions of the alkali atoms with the buffer gas resulting in decrease of the amplitude and significant broadening of the dark resonance. Thus the scheme proposed in [5] yielded practically only a small (1.4-fold) increase of the amplitude [7] compared to the usual σ^+-polarized light waves configuration.

In order to prevent atoms from leaving the working sublevels and thus enhance the amplitude and contrast, we propose a new method, based on the use of a two-frequency optical pumping, as shown in Figure 1 (pumping scheme with a similar spatial configuration was considered in another context [9]).

Let us suppose that ^{87}Rb atoms in a cell interact with the linearly-polarized laser field (the pumping field)

$$\vec{E}_{pump} = \frac{\vec{e}_z}{2}\left(E_3 \exp\left[i(k_3 x - \omega_3 t)\right] + E_4 \exp\left[i(k_4 x - \omega_4 t)\right]\right) + c.c. \quad (3)$$

One of the components of the pumping field is tuned in resonance with the $|F = 2\rangle \rightarrow |F' = 2\rangle$ transition and the second component is tuned in resonance with the $|F = 1\rangle \rightarrow |F' = 1\rangle$ transition, both of these transitions belonging to the D_1-line (see Fig. 2).

In this case, atoms are not pumped out from the working levels $|1\rangle = |F = 1, m = 0\rangle$ and $|2\rangle = |F = 2, m = 0\rangle$, since the corresponding Clebsch-Gordan coefficients and, hence, transition dipole matrix elements are equal to zero [10]. As a result, after a few optical pumping cycles (coherent excitation followed by spontaneous relaxation of the optically excited state) all the atoms will be accumulated in the working sublevels $|1\rangle$ and $|2\rangle$. Note that the two frequency components of the pumping field don't need to be correlated.

Suppose now that we switch on the weak (compared to the pumping field) probe field

$$\vec{E}_{probe} = \frac{\vec{e}_{+1}}{2}\left(E_1 \exp\left[i(k_1 z - \omega_1 t)\right] + E_2 \exp\left[i(k_2 z - \omega_2 t)\right]\right) + c.c., \quad (4)$$

which is circularly polarized and consists of two correlated frequency components tuned in resonance with the transitions from the ground state components to the excited states with $J' = 3/2$ (see Fig. 2). Since all the atoms are

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accumulated in the working sublevels, the contrast and amplitude of the probe beam absorption signal are greatly enhanced.

We have performed numerical calculations of the absorption in a ^{87}Rb vapor cell at room temperature. The density matrix approach is used. We take into account the real hyperfine (hf) and Zeeman structure of the states involved as well as the exact values of the probabilities of the optically-induced one-photon transitions and spontaneous relaxation of the optically excited states. Effects of the thermal motion of atoms (Doppler broadening) also have been taken into account.

For ^{87}Rb at 300 K the Doppler widths of the D_1 and D_2 lines are about 400 MHz, what is more then the hf splitting of the excited states with $J' = 3/2$, but less then the hf splitting of the excited states with $J' = 1/2$ (about 800 MHz).

The results of numerical calculations presented in Figure 4 are obtained in the limit when of the optical transition width $\gamma = \gamma_{sp}/2$, where $\gamma_{sp} = 3.6 \times 10^7$ s^{-1} is the spontaneous relaxation rate of the excited state of the Rb atom. In a general case $\gamma = \gamma_{sp}/2 + \gamma_{col}$, where γ_{col} is the contribution from collisions of the Rb atoms with the buffer gas. Typically, $\gamma_{col} < \gamma_{sp}$ for the buffer gas pressure of order of or less than few Torr. However, the buffer gas pressure $\sim$1 Torr is optimum, since it corresponds to the minimum width of the $|1\rangle \rightarrow |2\rangle$ transition between the working levels [11], provided that the relaxation induced by collisions of the Rb atoms with the cell walls is negligible. The quantitative measure of the importance of the wall relaxation is given by the parameter [12] $\mu = \{D/[L^2(W + D\delta k^2)]\}^{1/2}$, where D is the diffusion coefficient, L is the characteristic cell size, W is the rate of the probe-field induced optical pumping, and $\delta k = k_1 - k_2$. The inequality $\mu \ll 1$ means that the thickness of the boundary layer (where the relaxation of the coherence between the working levels is dominated by collisions with the cell walls) is much less than L, and, in average, the wall relaxation is negligible. Note that μ decreases as the laser intensity increases. For the buffer gas pressure $\sim$1 Torr, that corresponds to $D \sim 100$ cm^2/s, and $L \sim 1$ cm, the values of $\mu < 0.3$ are attained for the probe laser intensity of order of few dozens μW/cm^2 or higher (so that $W \geq 10^3$ s^{-1}). We have to reiterate that such a low pressure of the buffer gas provides the optimum balance between the Dicke narrowing and spin relaxation for the $|1\rangle \rightarrow |2\rangle$ transition between the working levels [11].

We have performed numerical calculations for $\gamma > \gamma_{sp}/2$ (the extra broadening may be due to collisions as well as to a large bandwidth of the laser radiation). The results are qualitatively the same, only the laser intensity should be rescaled in inverse proportion to the new value of the absorption profile (the convolution of the broadened Lorentzian and the thermal distribution of the atomic velocities). Relaxation rate Γ of coherences between the different hyperfine- and Zeeman sublevels of the ground state was taken to be equal to $\Gamma \approx 200$ s^{-1}. The depolarization rate in ground state is supposed to be equal to Γ.

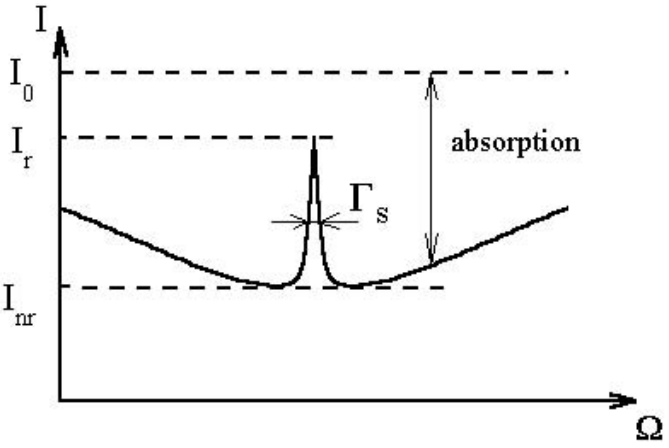

Fig. 3. Qualitative picture showing the dark resonance line shape. Γ_s is a width of dark resonance.

Let us denote the total population in excited states (for the σ^+ excitation scheme), or the total population on all the sublevels of the $J' = 3/2$ excited state (for the scheme with transversal pumping) as ρ_e. We find ρ_e from the density matrix equations. Then the absorbed power δU_{probe} of probe field is equal to:

$$\delta U_{probe} = \gamma\, \hbar\omega\, N\, \rho_e, \tag{5}$$

where $\hbar\omega$ is the optical transition energy, N is a total number of active atoms. The "absorbed photodetector current" is equal to the difference between the photodetector current without (I_0) and with (I) the gas cell (see Fig. 3):

$$I_0 - I = \delta U_{probe} \frac{e}{\hbar\omega} \kappa = \gamma\, e\, N\, \rho_e\, \kappa. \tag{6}$$

Here e is elementary charge, $\kappa \approx 1$ — effective quantum efficiency. In our calculations we suppose that the vapor cell contains $N = 10^{11}$ Rb atoms, that is typical for a cell of volume $\sim$10 cm^3 at 300 K [13].

The *amplitude* A of the dark resonance is defined as the difference between the photodetector current I_r on the two-photon resonance condition and the photodetector current I_{nr} outside the dark resonance (i.e., for $|\Omega| \gg \Gamma_s$), but still under the one-photon resonance condition for the optical transition. The *contrast* C is the ratio of the amplitude A to the absorbed current $I_0 - I_{nr}$.

The results of numerical calculations are shown in Figure 4. It shows that the amplitude-to-width ratio for the transversal pumping scheme is one order of magnitude higher than for the σ^+-polarized beam only.

Figure 4d shows the amplitude-to-width ratio, divided by square root of intensity (that determines the figure of merit of quantum frequency standard [13] in the case when the noise is the shot noise). Standard stability estimations [13] demonstrate that the best short-term stability attainable with this new scheme is $\sigma_y \leq 10^{-13}/\sqrt{\tau}$.

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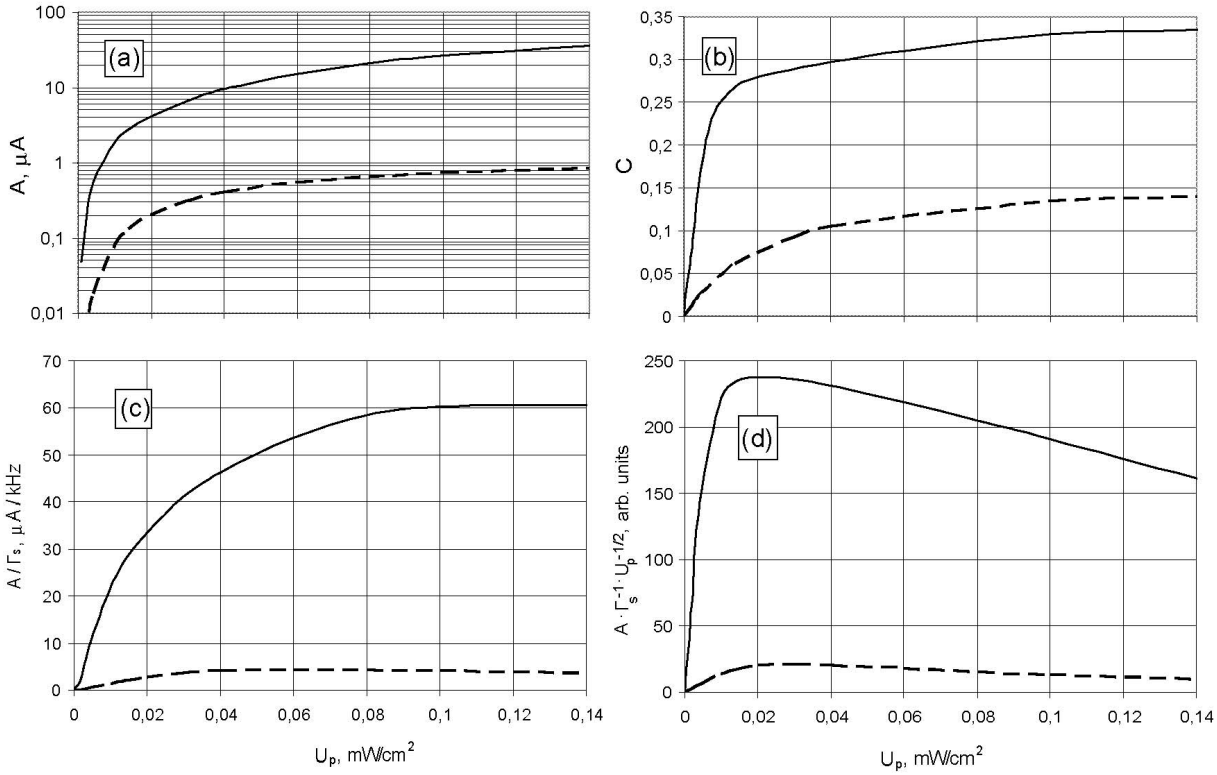

Fig. 4. (a) Amplitude, (b) contrast, (c) amplitude-to-width ratio, (d) amplitude-to to-width ratio, divided by the square root of the probe field intensity of the dark resonance versus probe field intensity U_P. Solid line is for the novel scheme involving perpendicular pumping beam with the intensity $U_0 = 10$ mW/cm^2 (in this case about 90% of atoms are accumulated in the working levels). Dashed line is for the traditional scheme involving the σ^+-polarized probe beam on D_1-line only.

References

1. B.D. Agap'ev et al., Phys. Usp. **36**, 763 (1993)
2. E. Arimondo, in *Progress in Optics*, edited by E. Wolf (North-Holland, Amsterdam, 1996), Vol. 35
3. J. Kitching et al., IEEE Trans. Instrum. Meas. **49**, 1313 (2000)
4. M. Merimaa et al., J. Opt. Soc. Am. B **20**, 273 (2003)
5. A.V. Taichenachev et al., JETP Lett. **80**, 236 (2004)
6. C. Affolderbach et al., Phys. Rev. A **65**, 043810 (2002)
7. S.V. Kargapoltsev et al., Laser Phys. Lett. **1**, 495 (2004)
8. D. Meshede et al., Phys. Rev. A **56**, R1063 (1997)
9. N.D. Bhaskar, IEEE Trans. Ultrason. Ferroelectr. Frequency Control **42**, 15 (1995)
10. J. Deng, IEEE Trans. Ultrason. Ferroelectr. Frequency Control **48**, 1657 (2001)
11. B.D. Agap'ev, M.B. Gorny, B.G. Matisov, Pis'ma Zh. Tekhn. Fiz. **12**, 315 (1986)
12. M.B. Gornyi, D.L. Markman, B.G. Matisov, Radiotekhn. Elektr. **31**, 1780 (1985)
13. J. Vanier, C. Audoin, *The Quantum Physics of Atomic Frequency Standards* (Adam Hilger, Bristol, 1989)