Two-frequency Pumping in ^{87}Rb Atomic Beam Frequency Standard with Laser Pumping/Detection for Space Application

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***Abstract*— We present our study on a two-frequency laser pumped ^{87}Rb atomic beam frequency standard for space applications. Two-frequency pumping was studied experimentally with using D_2 – line for the most efficient scheme (2-2' σ; 1-1' π) and proposed by us (2-2' σ; 1-0' σ) scheme. The achieved efficiency for two-frequency pumping using a new scheme was equal to 95%. In the shot noise limit we could achieve instability of $\sigma_y(\tau) \le 1\cdot10^{-13} \cdot \tau^{-1/2}$ in our breadboard of Rb atomic beam frequency standard.**

I. Introduction

The consideration of atomic states' energetic structure and relative probabilities of alkali atoms' optical transitions shows that the efficiency of one-frequency pumping is limited and can't be large since, when using the one-frequency excitation, a part of atoms does not interact with the light due to the hyperfine splitting of the ground state.

A great advantage of laser methods for creating a population inversion is the opportunity of accumulating all beam's atoms at a single magnetic sublevel ($|F_s, m_{Fs} = 0>$). This is achieved in method of two-frequency pumping which was proposed in [1] and experimentally proved for ^{133}Cs atomic beam in a number of works [2-4].

A well-grounded theoretical model was presented in [5] to evaluate the pumping efficiency of two-laser pumping schemes, taking into account optical, ground and excited states hyperfine and Zeeman coherences, neighboring transitions and fluctuating laser fields.

Two-frequency pumping scheme is based on using a forbidden optical $|F_s, m_{Fs} = 0> - |F' = F_s, m_{F'} = 0>$ transition and simultaneous excitation of atoms from two hyperfine sublevels of the ground state. The radiation of the laser adjusted to the $|F_s> - |F' = F_s>$ transition should have a linear π - polarization (**E** || **B**). The second laser with the arbitrary polarization is adjusted to the hyperfine $|F_s \pm 1> - |F'>$ component of the same or other D – line. Since a probability of dipole transition $|F_s, m_{Fs} = 0> - |F' = F_s, m_{F'} = 0>$ is always equal to zero, as a result of simultaneous excitation of atoms from two hyperfine sublevels of the ground state, all atoms will be repumped to the one of operating $|F_s, m_{Fs} = 0>$ sublevels. Compared to the magnetic selection of atoms, the two-frequency pumping can give a gain in the inversion of the operating sublevels' populations by 2(2I+1) times (I = 3/2 for ^{87}Rb and I = 7/2 for ^{133}Cs), i.e. by 8 times for Rb and 16 times for Cs discriminator.

Compared to the optical selection of atoms by one-frequency pumping this gain is as follows: 2.7 times for ^{87}Rb and ~ 6 times for ^{133}Cs atom. Let us note that the maximum efficiency for one-frequency pumping in the Rb beam is achieved with the (2-2' σ) scheme (D_1 or D_2 line) and is equal to 41.3 % [6]. For the ^{133}Cs beam such a situation takes place with (4-4' σ, D_2) scheme (15.5 %) [7].

The achievement of 100 % efficiency for two-frequency pumping is, however, related to realization of a number of conditions concerning intensity and width of both lasers' line, interaction time and correct selection of pumping transitions. As far as we know, in experiments performed with ^{133}Cs beam, 100 % pumping efficiency isn't achieved up to now.

The objective of studies is to experimentally determine the opportunity of achievement of 100-percent efficiency for two-frequency pumping in ^{87}Rb atomic beam. The advantages of using ^{87}Rb as a working substance when developing a high-stable small-size atomic beam frequency standard with laser pumping were shown in [8] where the efficiencies of main schemes for pumping and detection in ^{87}Rb and ^{133}Cs beam were compared.

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II. TWO-FREQUENCY PUMPING IN ^{87}Rb BEAM

A. Standard two-frequency pumped schemes in ^{87}Rb using the forbidden transitions

In [6] we calculated two-frequency pumping for ^{87}Rb atomic beam using the “rate” equations’ formalism. One assumed the absence of coherence effects and “atom leakage” which may be appeared in the simultaneous excitation of neighbouring hyperfine transitions at the wings of the pumping transition’s contour.

The pumping efficiency for |1,0> and |2,0> sublevels of the ^{87}Rb atom is calculated as a dependence of the relative population difference of these sublevels, $\Delta n_{o\text{-}o}/n_o$ ($\Delta n_{o\text{-}o} = |n_{1,0} - n_{2,0}|$), on certain unified parameter, τ_{eff}, taking into account intensity and spectral width of the laser line, absorption linewidth in the atomic beam, time of beam atoms interaction with light-wave, degree of emission and absorption contours overlapping,.. The interaction parameter, τ_{eff}, is numerically equal to the number of photons absorbed by the atom over t time: $\tau_{eff} = 2\ (\pi \ln 2)^{1/2}\, r_0\, c\, f_J\, L/N_J \cdot I_0\, \rho\, t/\Delta\nu_{abs} = S_\mu^{JFs} \cdot t \approx 10^{-3}\, I_0\, \rho t/\Delta\nu_{abs}$, I_0 [phot/(s·cm^2)]. Fig. 1 presents the main calculation results of the two-frequency pumping efficiency for possible schemes in ^{87}Rb atom with using the forbidden transitions. The most efficient scheme have been identified: 2-2’ σ (D_1 or D_2) ; 1-1’π (D_2)

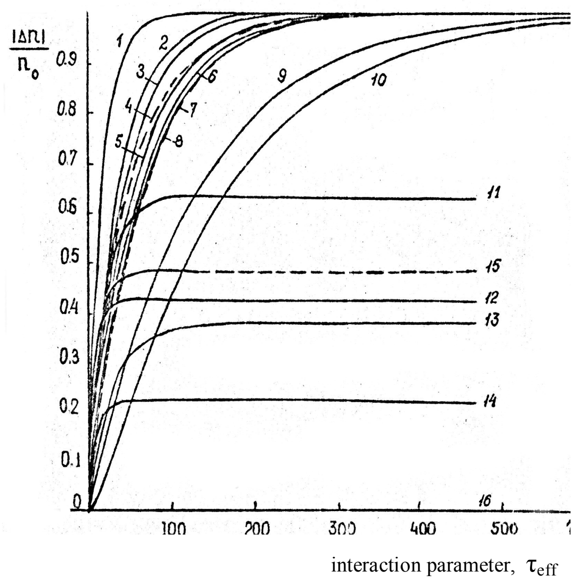

Figure 1. Efficiency of various schemes for two-frequency laser pumping of ^{87}Rb atomic beam as a dependence on τ_{eff} [6]:

1 - D_2, 1-1’π; D_2 (D_1) 2-2’σ	11- D_2, 1-1’π; D_2, 2-1’π
2 - D_2, 2-2’π; D_1, 1-2’π	12 - D_2, 1-1’π; D_1, 2-1’π
3 - D_2, 1-1’π; D_2 (D_1) 2-2’π	14 - D_1, 1-1’π; D_1, 2-1’π
4 - D_2 (D_1), 2-2’π; D_1, 1-1’σ	15 - D_2, 1-1’π; D_1(D_2), 2-2’π
5 - D_2 (D_1), 2-2’π; D_2, 1-2’π	
6 - D_2, 2-2’ π; 1-2’ σ	16 - D_1, 1-1’ π; D_1(D_2), 2-2’ π ($\Delta n_{o\text{-}o} = 0$)
9 - D_1, 1-1’ π; D_2, 2-1’σ	
10 - D_1, 1-1’π; D_1, 2-1’σ	

11÷14 - schemes of two-frequency pumping with accumulation of atoms in | 1,0 > - state and population of “pockets” | 2, ±2 > ;

15 – scheme of two-frequency pumping with a concurrence of accumulation in | 1,0 > and | 2,0 > states

The scheme for pumping by D_1 - line using D_1, 1-1’π and D_1 (D_2), 2-2 π - transitions results the equal population of operating sublevels and pumping efficiency equal to zero.

Note that 2-2’σ (D_1 or D_2) scheme for one-frequency pumping provides the maximum pumping efficiency (41.3%) when the interaction parameter is $\tau_{eff} \approx 70$ (Fig. 2) [6]. The polarization of the laser beam: σ ($\mathbf{e}_\lambda \perp \mathbf{B}$). The orientation of $\mathbf{k}_\lambda$ and $\mathbf{e}_\lambda$ vectors is shown in Fig. 5. The value of magnetic field within a pumping region, B_{op}, exceeds 0.8 G. We used this pumping scheme when creating a breadboard of the Rb atomic beam frequency standard with laser pumping [8].

When exciting at the (1-1’π, D_2) transition, the pumping efficiency achieves only 17,8 %.

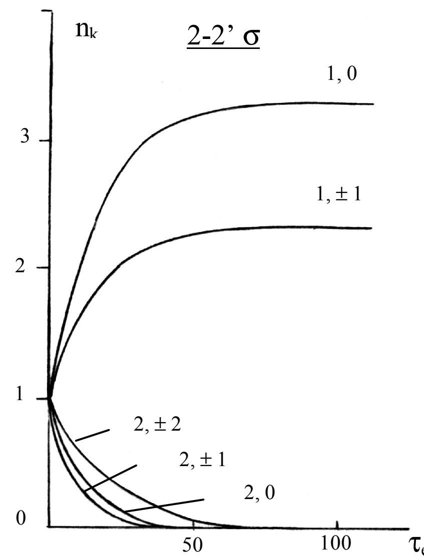

Figure 2. Population distributions $n_k = f(\tau_{eff})$ of the |1, m_F > and |2, m_F> ground state sublevels at laser pumping ^{87}Rb atoms in the beam by D_2 line. Pumping transition: 2-2’ σ.

The pumping schemes with one laser are characterized by restricted efficiency and fast pumping. Two-frequency schemes give maximum efficiencies with slow pumping. It increases significantly a contribution of slow atoms to the frequency standard’s signal. The detection at the cyclic transition in these schemes results in the distortion of the Maxwell distribution and the appearance of the weight multiplier, 1/v, in the function of atomic velocity distribution.

B. New two-frequency pumping scheme inherent in ^{87}Rb using a cyiclic transition

The cyclic (1-0’) transition is, as a rule, only used for the detection in the atomic discriminator scheme with pumping by a short-wave |1>- $^2P_{3/2}$ component since it does not transfer atoms to the |2,m_{Fs} > - state. The calculations show, however, that this excitation scheme redistributes atoms among the |1,m_{Fs}> ground-state’s sublevels and in such a way that |1,0> and |2,0> sublevels appear to be pumped by 25 %. It is Zeeman’s pumping of the |1,0>

sublevel at the expense of |1, ±1> ones. This exceed by 1.4 times the results of one-frequency pumping when using a standard additional pumping (1-1'π) transition (17.8 %) and well higher (by 1.6 times) that in the best one-frequency pumping scheme for ^{133}Cs atoms (15.5%). The cyclic (1-0') transition is proposed by us to use as an additional one when using the two-frequency excitation.

Population distributions $n_k = f(\tau_{eff})$ of the |1, m_F > and |2, m_F> ground state sublevels at laser pumping ^{87}Rb atoms by D_2 - line on the additional transitions are presented in Fig. 3, 4.

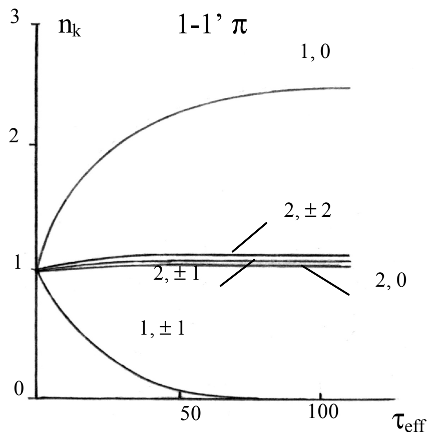

Figure 3. Population distributions $n_k = f(\tau_{eff})$ of the |1, m_F > and |2, m_F> ground state sublevels at laser pumping ^{87}Rb atoms in the beam by D_2 line. Pumping transition: <u>1-1' π.</u>

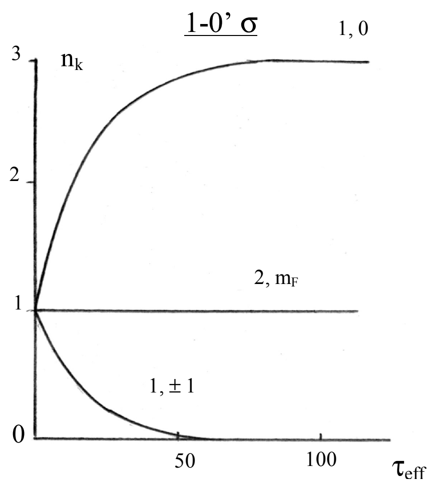

Figure 4. Population distributions $n_k = f(\tau_{eff})$ of the |1, m_F > and |2, m_F> ground state sublevels at laser pumping ^{87}Rb atoms in the beam by D_2 line. Pumping transition: <u>1-0' σ.</u>

Examination of the population distributions, $n_k = f(\tau_{eff})$, of |1,m_F> and |2,m_F > ground state's sublevels, when exciting at (1-1' π, D_2) or (1-0' σ, D_2) transitions, shows their likeness. However, the latter scheme has some advantages.

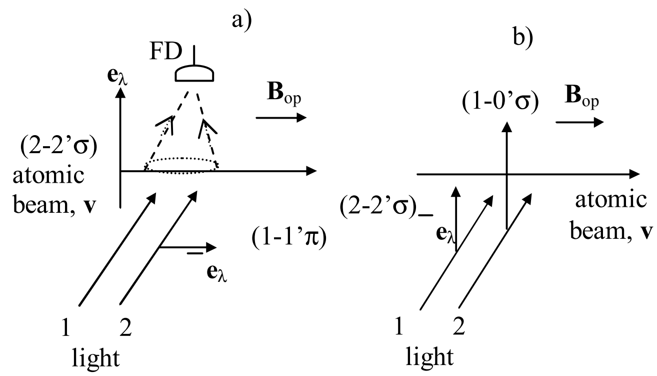

Figure 5. Orientation of the vectors $\mathbf{k}_\lambda$ (light), $\mathbf{e}_\lambda$ (polarization) and **v** (atom velocity) with reference to $\mathbf{B}_{op}$ vector of a weak magnetic field within pumping zone.

1) Pumping rate. Discriminator's signal-to-noise ratio.

When exciting at the (1-0'σ) transition the populations of the |2, m_{Fs}> sublevels stay constancy. The transfer of atoms to |2, m_{Fs}> - states does not take place This circumstance leads to more pumping rate in the case of two-frequency pumping on |1,0> sublevel with using (2-2' σ; 1-0' σ) scheme. The discriminator's signal-to-noise ratio is increased when detection of microwave "0-0" resonance on |2>- |3'> transition because of an un-pumping atoms number on |2,0> sublevel at the detection zone is equal zero. In result, there is not a transfer of the pumping laser frequency noise into the detection region.

In pumping at the (1-1'π) transition 25% of atoms were being on the |1,±1> sublevels transfer to the |2, m_{Fs}> state in each exciting cycle. As a result, the pumping rate in the case of two-frequency pumping on the |1,0> sublevel with using (2-2' σ; 1-1' π) scheme is reduced. The discriminator's SNR value is also reduced because of an un-pumping atoms number on the |2,0> sublevel at the detection zone is not equal zero though excitation at the (2-2' σ) transition devastates the | 2> state completely.

2) SNR value at the frequency lock loop system of the additional laser.

When using the cyclic transition (1-0'σ) as addition one in the case of two-frequency pumping the SNR value at the optical channel of this laser's frequency lock loop system is more because a measured number of the re-emitted photons per atom achieves β ~ 35 phot/at. In pumping at the (1-1'π) transition β_{max} ~ 6 phot/at [6].

3) Rate and efficiency of two-frequency pumping.

In two-frequency pumping schemes with *successive* excitation of atoms from two hyperfine sublevels of the ground state on the main and additional transitions the pumping

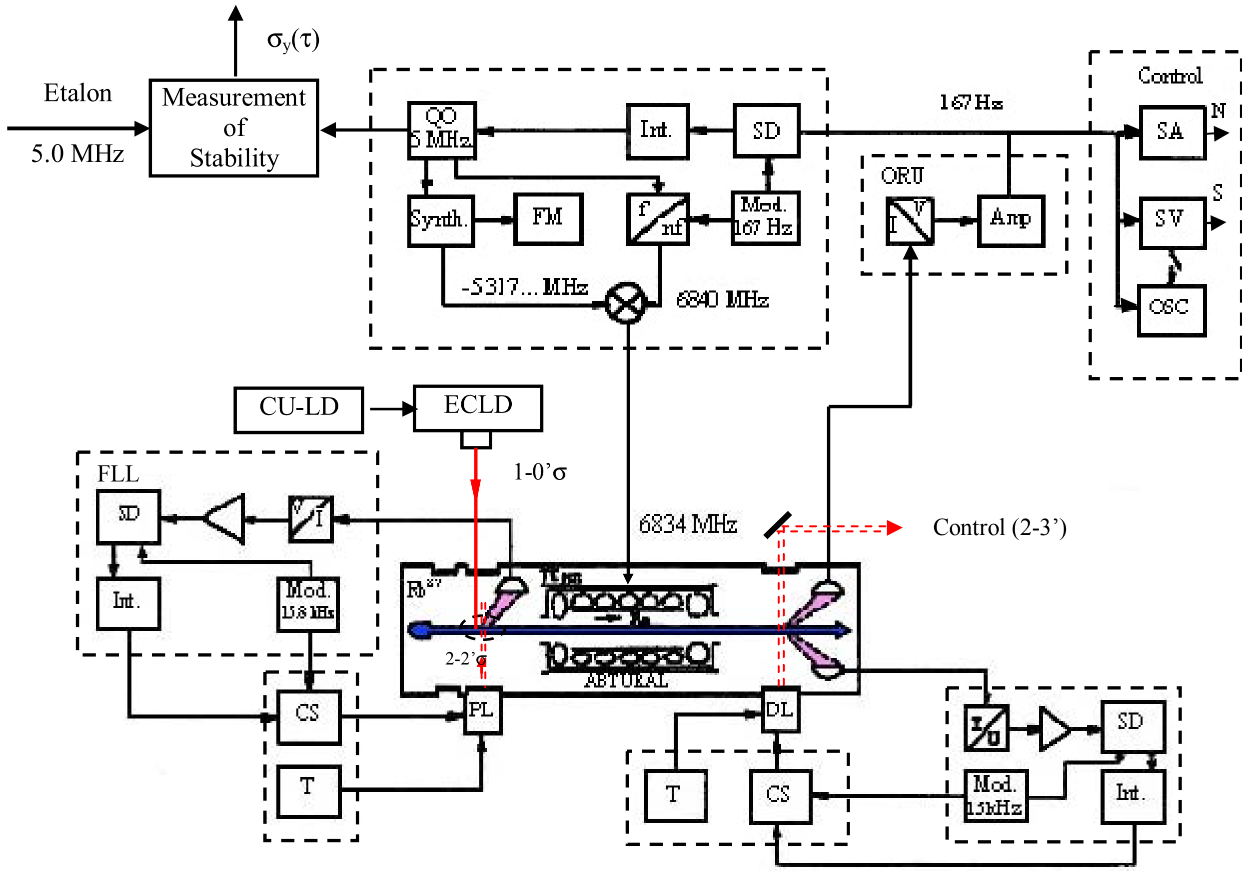

Figure 6. Block diagram of a breadboard of the Rb atomic beam frequency standard with two-frequency laser pumping. QO - quartz. oscillator, Synt – synthesator, FM – frequency meas., Int – integrator, SD - synchronous detector, Mod – modulator, Amp – amplifier, ORU - optical recording unit , SA spectrum analyzer, SV- selective voltmeter, Osc – oscilloscope, CS - current source, T – thermoregulator, PL - pumping laser, DL – detection laser, ABT - atomic beam tube, ECLD – external cavity laser diode, CU-LD – control unit of the ECLD.

TABLE I. CHARACTERISTICS OF THE MAIN **(2-2' σ)** AND TWO AUXILIARY TRANSITIONS, **(1-1' π)** and **(1-0' σ)**. RESULTS OF THE CALCULATION AND MEASUREMENTS.

F_s – F' (D_2)	$\Delta n_{(0-0)}/n_0$ %	β_{max}	$\|\Delta n \cdot \beta\|$	τ_{eff}	P_{opt}	Two-frequency Pumping $\Delta n_{(0-0)}/n_0$, %; cycles				Experiment ($\Delta n_{(0-0)}/n_0$, %)	Det.
						I	*II*	*III*	*IV*		
1-1' σ	*- 26.2*	*6*	*157.2*	70	5	*strong un-pumping transition*					2-3'
1–0' σ	25	33 (*cycl*)	(~830)	70	2	66.25	91.25	100	-	$S_{un-pump}$= 0 N_{L-OP} ~ 0 95.2 % (2.3 · 41.3%)	
2-2' σ	**41.3**	2	82.6	70	5						
1-1' π	17.8	6	106.5	70	5	60	81.6	96.1	99.5	$S_{un-pump}$> 0 N_{L-OP} >> 0 72.1 % (1.7 · 41.3%)	

efficiency 66.25% and 60% can be achieved when using (2-2' σ; 1-0' σ) and (2-2' σ; 1-1' π) schemes accordingly (one cycle).

In the case of two-frequency pumping with *simultaneous* excitation of atoms from two hyperfine sublevels 100% - pumping efficiency can be achieved when using (2-2' σ; 1-0' σ) scheme during 3 cycles. When using (1-1' π) transition as additional one the "0-0" transition's inversion achieves only 99.5% even after four pumping cycles.

Comparative characteristics of the main (2-2' σ) and two auxiliary transitions, (1-1'π) and (1-0'σ), as well as calculated data on two-frequency pumping with using both schemes are presented in Table 1. One can see that calculation shows a significantly higher rate and efficiency of two-frequency pumping when using a scheme with (1-0' σ) – transition.

Some deficiency of using the (1-0'σ) transition in two-frequency pumping is possibility of overlapping with (1-1'σ) component which is away from (1-0'σ) one on frequency interval 72 MHz and represent the strong un-pumping transition for pumping |1,0 > sublevel ($\Delta n_{o\text{-}o} / n_o = -26.2\%$, $\Delta n_{o\text{-}o} = n_{1,0} - n_{2,0}$). It is the strongest (as regards the $|\Delta n \cdot \beta|$ parameter) transition within a spectrum of the D_2 line's hyperfine components ($|\Delta n \cdot \beta| = 157.2$ [6]). However, with enough resolution of (1-0') and (1-1') components within a pumping region (proper collimation of atomic and light beams and narrow laser line), in the absence of overlapping these lines' contours, the proposed variant of two-frequency pumping – with using (1-0' σ) transition – appears, as is shown above, to be more efficient than the standard one.

IV. EXPERIMENTAL STUDIES OF TWO FREQUENCY PUMPING IN Rb-ABT

A. Block diagram of the atomic beam discriminator

The specific features of our frequency standard breadboard (Rb atomic beam tube, ABT, and its parameters, laser modules with frequency control systems, and optical detection assemblies) as well as our results with the two-lasers' scheme (with one-frequency pumping) were described in [8]. Additional block diagram is presented in Fig. 6.

In this work, we studied two efficient variants of two-frequency pumping with the D_2 - line of a diode laser in the Rb discriminator: (2-2' σ; 1-1' π) scheme with a forbidden (1-1' π) transition and a new (2-2' σ; 1-0' σ) scheme using a cyclic (1-0' σ) transition. In these variants, a constant magnetic field, $B_{op} > 0.8$ G parallel to the atomic beam in the pumping region is needed to eliminate the CPT effect on (2-2' σ) and (1-0' σ) hyperfine transitions.

For pumping (on 2-2' σ transition) and detection (on cyclic 2-3' one), we used the foreign diode lasers (HL 7859 MG; a line width of ~ 8 MHz) and an additional domestic external cavity laser diode (ECLD; a line width of 0.8 MHz) - for two-frequency pumping – on (1-1' π) or (1-0' σ) transitions. As a result, the effect of atoms' loss from the two-frequency cycle because of the wings contours' overlapping did not appear.

Measured data on two-frequency pumping with using both schemes, (2-2' σ; 1-1' π) and (2-2' σ; 1-0' σ), are presented in Table. 1. These measurements show a significantly higher rate and efficiency of two-frequency pumping when using a scheme with (1-0' σ) – transition.

We have shown experimentally the increase in the discriminator's "0-0" transition signal when using two-frequency pumping: by 1.74 times for (2-2' σ; 1-1' π) scheme and by 2.3 times for the (2-2' σ; 1-0' σ) scheme with a cyclic transition compared to one-frequency pumping on (2-2' σ) transition. In the proposed scheme, the achieved population inversion of |1,0> and |2,0> ground state sublevels was of 95 %.

In the shot noise limit, with two-frequency pumping, one can realize in our frequency standard breadboard a short-term frequency instability $\sigma_y(\tau) < 1\cdot10^{-13}\cdot \tau^{-1/2}$, with a zero-pedestal of a resonance signal $\sigma_y(\tau) \sim 4.4\cdot10^{-14}\cdot \tau^{-1/2}$.

V. CONCLUSION

We shown that it is possible to realize two variants of efficient two-frequency pumping in the ^{87}Rb atomic beam: A – on (2-2' σ) and (1-1' π) – transitions, B – on (2-2'σ) and (1-0' σ) – ones. The second variant is only possible for ^{87}Rb and is realized with a lesser τ_{eff} parameter compared to the first one. One has experimentally obtained a signal gain at the AD's output by 1.74 times for A - variant and by 2.3 times for B - variant, i.e. the inversion of "0-0" – transition's populations was achieved equal to 95.2 percent.

Use of two-frequency pumping is connected with significant technical complications for atomic discriminator and its electronic circuitry caused by introduction of the third laser with its frequency control systems. For achieving 100% pumping one should observe a number of limitations related to the divergence of atomic and laser beams.

In connection with it, use of two-frequency pumping for improving the AD-ABT's figure of merit is more advisable for the ABT with ^{133}Cs atomic beam where the efficiency of the best one-frequency pumping scheme is initially 15.5% only. The total populations' inversion with two-frequency pumping results in AD' signal gain by 6.5 time. As for the ABT on ^{87}Rb atomic beam, as is shown in the work published in [6], when using one-frequency pumping, the inversion of operating sublevels' populations achieves initially 41.3%; therefore going to two-frequency pumping will result in a gain of 2.4 times only.

The significant advantages of ^{87}Rb as a working substance compared to ^{133}Cs (as regards pumping/detection efficiency, value of atomic flow, hyperfine components' spectrum, cyclic transition's power, etc.) show that is essentially lesser advisable to realize the Rb discriminator using three-laser scheme than in the Cs case.

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