Study of a ^{87}Rb Vapour Discriminator with Laser Pumping for a High Stability Onboard Frequency Standard

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Abstract - **We report on our progress towards the realization of a high-performance laser-pumped Rubidium vapour-cell atomic frequency standard for satellite navigation. The conversion process of the laser's FM-AM noise which degrades the SNR of a gas-cell discriminator with ^{87}Rb and buffer gases was experimentally studied as a function of laser's intensity and its frequency using the double radio-optical resonance scheme (DROR) operating on two optical transitions: |2>- $^2P_{3/2}$ or |1>- $^2P_{3/2}$. The new method is proposed and realized for fine tuning of a laser frequency to the value corresponding to the minimum value of FM-AM conversion noise. While using this method, the RFS breadboard is built.**

I. INTRODUCTION

As is known, one of promising directions for improving accuracy parameters of Rubidium gas-cell frequency standards (RFS) which are widely used in GNSS (GPS, GLONASS, GALILEO) is to utilize advantages of laser pumping. The objective of studies being conducted at RIRT in the framework of INTAS-CNES cooperation is creation a high-stability small-size RFS for the satellite navigation proving frequency instability less than $1{\cdot}10^{-12}$ over 1 s and $1{\cdot}10^{-14}$ over 10^4 s.

The main sources of RFS instability are considered in many works [1-7]. These works show that the matter-of-principle limiting factors are light shift and laser's frequency noise.

The clock's instability related to the light shift can be reduced by optimizing absorption cell (size, buffer mix, buffer gas pressure and temperature), pumping light's intensity and fluctuation level, by improving a laser frequency control technique (frequency, modulation index) as well as by using methods for suppression of the light shift [8]. The problem of laser's frequency noise impact of the RFS instability was studied, for the most part, at the theoretical level [3,4,10,11]. The role of optical pumping was shown as regards the FM-AM noise conversion on the contour of optical absorption line of atomic vapour with buffer gases.

The work is dedicated to the experimental investigation of such a factor as the impact of the process of converting the laser frequency noise into the amplitude one on DROR signal and SNR of a gas-cell discriminator with ^{87}Rb vapour and buffer gas mix. The conditions are being considered for minimization of FM-AM conversion noise as well as problems related to the realization of a high-stability RFS under these conditions.

II. ^{87}Rb VAPOUR DISCRIMINATOR WITH LASER PUMPING

A. Block diagram of a setup

The design of our breadboards of vapour discriminator and RFS was described in [7]. The discriminator with laser excitation is based on a modified industrial RFS with lamp pumping developed by RIRT's specialists. Spectral lamp and isotopic filter were replaced with an external laser diode source. The main setup's components with Rb discriminator are presented in Fig.1.

1 - Physical package.
Absorption cell (sphere Ø13 mm) filled with Rb^{87} vapour and buffer gas mix (Ar-Ne) with a total pressure of 17.3 Torr (P_{Ar} = 5.8 Torr, P_{Ne} = 11.5 Torr). The cell temperature is optimized and equal to 65 ^{0}C. The discriminator's thermostat has a two-stage temperature control with an accuracy of ~ $5{\cdot}10^{-3}$ ^{0}C. The cell is placed into the rectangular microwave cavity (H_{021}) being in the constant magnetic field ($H_0 \approx 0.08$ G).
Unit for optical recording with a photo-receiver device (PRD) including I-V converter. The PRD supports a constant photo-receiver's sensitivity up to the frequencies of ~ 35 kHz. The industrial shell-free Si-PR is used with selection of parameters.

8 - The laser source is a module containing laser diode (HL 7859 MG), micro-objective, micro-cooler, thermosensors. The operating mode is single-frequency, continuous. The generation line width of the laser diode is ~ 7.8 MHz. The laser beam cross-section is ∅2-4 mm, collimation is 10^{-2} [14]. The emission power at the operating mode was ~ 20 μW at the cell input. The laser ray is linearly polarized, its wave vector is oriented along $\mathbf{H_0}$ - field in the cell for providing efficient pumping.

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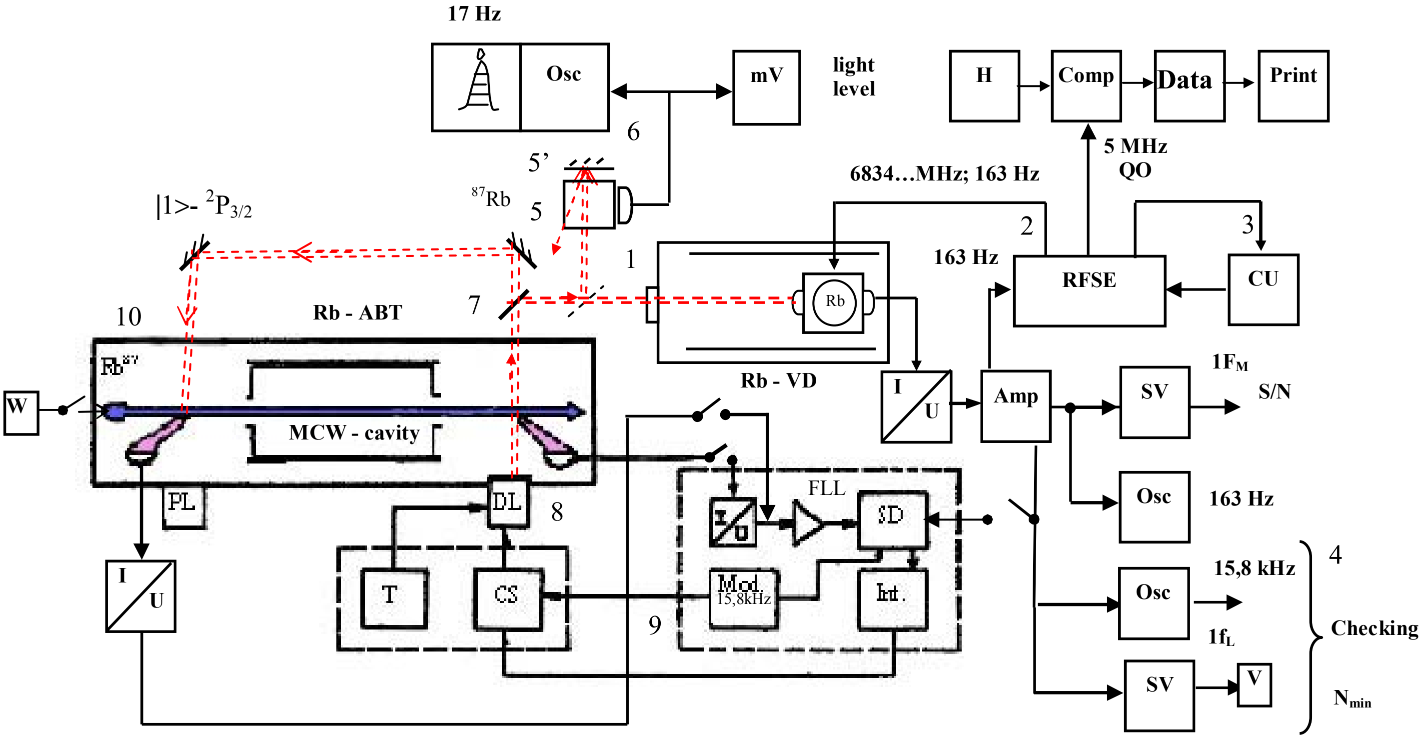

Figure 1. Block diagram of a breadboard of the Rb atomic vapour frequency standard with laser pumping. QO - quartz. oscillator, Int – integrator, SD - synchronous detector, Mod – modulator, Amp – amplifier, SV- selective voltmeter, Osc – oscilloscope, CS - current source, T – thermoregulator, FLL - frequency-lock loop, DL – laser diode, VD - gas-cell discriminator, CU - control unit, H - Etalon (H – generator), Comp – comparator, Print – printer, RFSE - electronic systems of RFS.

9 - Laser frequency discriminator with a system for automatic frequency control (AFC): electronic systems for active and passive (FLL; I, T) stabilization of laser's parameters and device for detecting the optical signal.

2, 3 - Adapted electronic circuitry from the industrial RFS of the traditional type for using an atomic discriminator (AD) in the regime of a frequency standard.

4 - Units for measurement and checking over the AD output signals at the modulation frequencies F_m = 163 Hz and f_m^L = 15.8 kHz.

5 - Additional gas cell containing ^{87}Rb without buffer gas (T = 22^{0}C).

6 – Unit for recording a Doppler absorption line' contour.

7 – Attenuator, mirrors for putting a laser emission to the main and additional gas cells.
Optical monochromator and video-checking device.

10 - Rb atomic beam tube (ABT) with laser pumping and detection [14].

The modulation frequency of the microwave excitation signal is F_m = 163 Hz. The frequency of laser's current (emission frequency) modulation is f_m^L = 15.8 kHz. These frequencies are selected taking into account $F_m << 1/\tau_{op} << f_m^L$ relation where τ_{op}^{-1} – pumping rate on the hyperfine transition [4, 10].

Setup represents the basis for development a combined Rb beam and cell clock-tandem with one laser pumping, that combines the advantages of both standards.

B. Method for measuring signals at the AD output as function of laser frequency f_L.

For realizing such goals as obtaining an optical absorption on line's contour, studying the dependence of laser frequency modulation conversion into the intensity modulation (FM-AM) on the line's contour with optical pumping in the AD, optimizing DROR signal and SNR value depending on laser frequency one should select a zero reading point for laser's frequency adjusting within the absorption line, Δf_L=0. As the initial point for laser frequency detuning, when measuring, one has adopted a frequency of the absorption line peak in the additional cell 5 (Fig. 1) containing ^{87}Rb only and therefore reproducible. This line's contour is not broadened through collisions and optical pumping and can easily be calculated.

The operating cell was irradiated by D_2 line. Such processes were studied as pumping and noise conversion on two optical transitions: |2> - $^2P_{3/2}$ and |1> - $^2P_{3/2}$.

For obtaining independent frequency marks of hyperfine transitions when pumping from |2> or |1> level's relative to the absorption line contour in the operating cell, the laser beam was transmitted through an atomic Rb beam (ABT). The superposed oscillograms of absorption lines' contours obtained for a cell without the buffer gas and resonances of atomic beam's fluorescence are shown in Fig. 2.

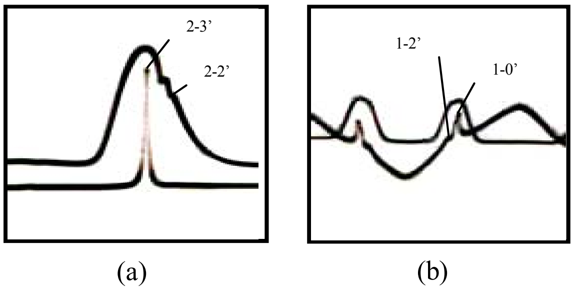

Figure 2. Oscillograms of absorption lines' contours for a cell without the buffer gas and resonances of atomic beam's fluorescence: a) $|2> - {}^2P_{3/2}$; b) $|1> - {}^2P_{3/2}$.

In addition, the Rubidium ABT was used for stabilizing a laser frequency (with specified Δf_L^0 detuning) against a fluorescent signal of the atomic beam.

In such a way, for obtaining DROR signal, frequency marks of hyperfine optical transitions relative to the contour of the operating cell's absorption line as well as for laser's active frequency stabilization against a narrow atomic line and its locking onto a specified mark, the laser beam was splitted into four channels: the part of emission was put to the operating cell, the other part – to the Rb–ABT atomic beam perpendicular to the beam (in the detection zone) and to the auxiliary cell with ^{87}Rb vapour without the buffer gas. The remaining emission part, using an optical fiber bundle, was put to the atomic beam (in the pumping zone) at the calculated small angle. This enable one, due to the Doppler shift, to perform fine adjustment and laser's frequency stabilization using the resonance of atomic beam fluorescence at any frequency being between non-shifted hyperfine components.

III. EXPERIMENTAL RESULTS

A. Contour of optical absorption line and DROR signal

Dependences of DROR signal amplitude and noise at the output of the ^{87}Rb vapour discriminator (at the modulation frequency of microwave field, F_m = 163 Hz) on laser emission frequency, f_L (current, i_L) were studied for two pumping schemes: $|2> - {}^2P_{3/2}$ and $|1> - {}^2P_{3/2}$.

Optical pumping changes a population of the initial level, and the absorption from this level is reduced. The change in absorption introduced by pumping is modulated by the modulation frequency, F_m, of the microwave field. Therefore, when retuning a laser's frequency, Δf_L (current, Δi_L), within a contour of the optical absorption line (~ 800 MHz, taking into account the broadening due to buffer gases; the appropriate current retuning is ~ 0.5 mA), the dependence of DROR signal on laser's frequency detuning, $S(F_m) = f(\Delta f_L)$, is, in fact, a contour of integral optical absorption line in the AD cell. The examples of absorption lines' contours, $S(F_m)$, when pumping on both hyperfine transitions, are given in Fig.3,4. The calculated Doppler contour of the line of absorption in the cell without the buffer gas, S_D, is also given ($T_{cell} = 65^0$C; $\Delta f_L = 0$ for maximum of S_D value). The absorption lines are non-uniformly broadened and strongly distorted by optical pumping.

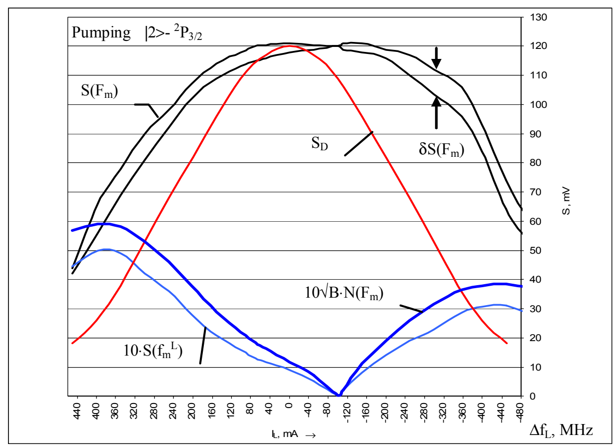

Figure 3. Contour of the absorption line in the operating cell and dependence of noise, $N(F_m)$, at the AD output on laser's frequency detuning Δf_L. Pumping $|2> - {}^2P_{3/2}$.

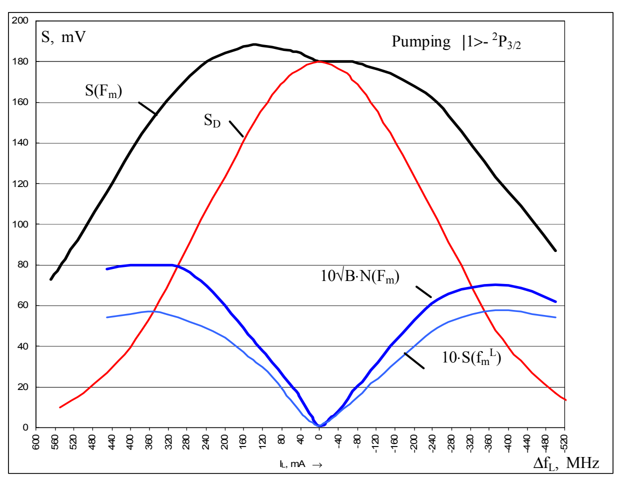

Figure 4. Contour of the absorption line in the operating cell and dependence of noise, $N(F_m)$, at the AD output on laser's frequency detuning. Pumping $|1> - {}^2P_{3/2}$.

Obtained dependences show that a laser's frequency corresponding to the absorption line's peak, $S(F_m)_{max}$, is shifted by buffer gases pressure and optical pumping relative to the center of the absorption line in the pure cell, $(S_D)_{max}$, in both cases (but with different sign).

B. Study of FM-AM noise conversion. DROR noise.

For studying a conversion of the laser's frequency noise into the amplitude one in optical pumping such a technique was used as that of additional calibrated frequency noise [2]. Its carrier was a weak frequency modulation of the laser frequency, f_L, applied for the laser's frequency stabilization (at f_m^L = 15.8 kHz). The modulation level could be checked and changed. The signal amplitude $S(f_m^L)$ measured at the AD output at 15.8 kHz frequency reflected a degree of conversion of the laser's frequency noise into the amplitude one on the absorption contour in optical pumping.

The dependence of the AD's signal at 15.8-kHz frequency, $S(f_m^L)$, on laser's frequency detuning, Δf_L, as well as that for AD's noise at F_m=163 Hz when modulation was switched off, $N(F_m)$, for both pumping schemes are presented in Fig. 3, 4.

It is shown the existence of a point (Δf_L^0) at which the DROR signal, $S(F_m)$, has a special feature and the noise at both frequencies (F_m and f_m^L for inserted noise) tends to the minimum value. The similarity of $N(F_m)$ and $S(f_m^L)$ curves confirms Camparo's thesis [11] on the impact of the fast frequency modulation on the fluorescence noise at low Fourier-frequencies. The maximum noise at the output of discriminator is observed at f_L frequencies corresponding to a half-width of the absorption line. Its value for $S(f_m^L)$ depends on the modulation depth which, however, is always less than a half-width of the optical absorption line. In average, when scanning a laser's frequency on absorption line's contour, the FM-AM conversion noise can change by ~ 100 times.

The points with minimum noise do not coincide with the maximum of the absorption line, $S_{max}(f_m^L)$, when pumping from |2> or |1> levels and are located near the non-shifted |2> - |2'> and |1> - | 1'> transitions, respectively. Only at these points, the maximum SNR value of discriminator is obtained. The Fig. 4, 6 show the case of pumping from the |1> level. When optimizing the discriminator's operating regimes, this pumping scheme proved to be more advantageous than |2>-$^2P_{3/2}$ one. The authors of the work [6] made the same conclusion.

The DROR signals' oscillograms (Fig. 5; F_m = 163 Hz) obtained with various detuning of a laser's frequency, Δf_L, show a change not only in the AD's amplitude noise, but also in the frequency noise causing it.

The point of the AD's minimum noise, Δf_L^0, accurately corresponds to the disappearance on the oscillograph traces of laser's frequency modulation (f_m^L = 15.8 kHz) and amplitude noise. The same pattern was observed at second harmonic's signals ($2F_m$ = 326 Hz) when closing the AD's frequency-lock loop. For |2>-$^2P_{3/2}$ pumping $\Delta f_L^0 \approx$ - 100 MHz in average. For |1>-$^2P_{3/2}$ pumping $\Delta f_L^0 \approx$ 0 MHz (in average). Obviously one of reasons for zero-detuning when pumping from |1> level lies in the fact that the cyclic, |1>-|0'>, transition is in reality open and takes a lesser part in pumping (absorption line's distortion) than the cyclic |2>-|3'> transition when pumping from |2> level. This is also confirmed when comparing a shape of absorption lines' contours shown in Fig.3, 4 for pumping from |2> and |1> levels.

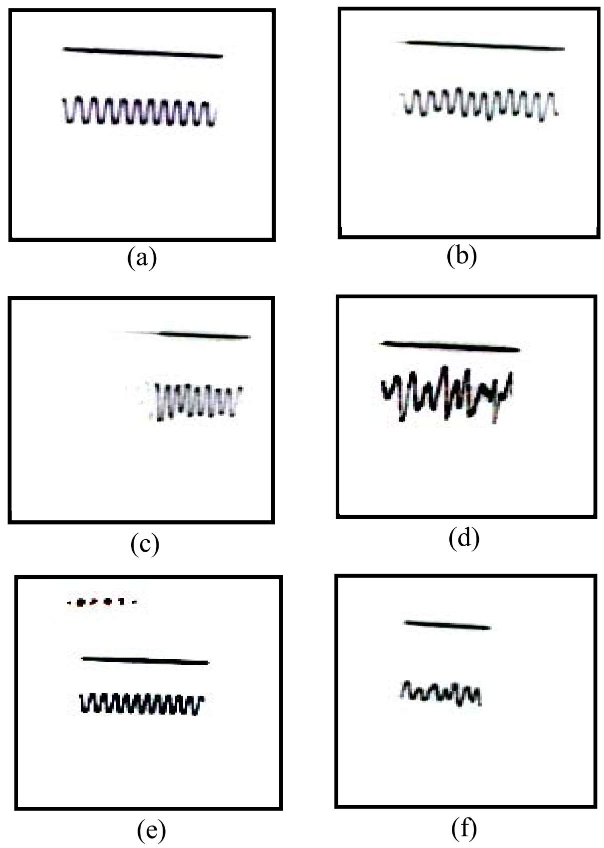

Figure 5. DROR signals' oscillograms at the different laser's frequency detuning Δf_L (F_m = 163 Hz). Pumping |2>-$^2P_{3/2}$: a) $\Delta f_L \approx$ -100 MHz, b) $\Delta f_L \approx$ 0 Hz, c) $\Delta f_L \approx$ - 254 MHz, d) $\Delta f_L \approx$ 254 MHz. Pumping |1>-$^2P_{3/2}$: e) $\Delta f_L \approx$ 0 MHz, f) $\Delta f_L \approx$ 70 MHz.

Many experimental data when changing the laser intensity or the way of laser beam across the resonator with the gas cell show that the laser's detunings Δf_L^0 for N_{min} and $S_{min}(f_m^L)$ points are not changed in spite of the catastrophic line distortion. The $N(F_m)$ and $S(f_m^L)$ dependences are very sharp near the zero value.

The physical nature of a sharp noise drop at some point of the absorption line can be explained as follows. When exciting a multilevel ^{87}Rb atom with the D_2 - line, a system of hyperfine optical transitions forming in the aggregate an absorption line's contour represents a double non-resolved V-system [11] (W). The value of FM-AM conversion noise at each frequency, f_L, is defined by the W-system's composition with two open pumping transitions and one cyclic transition as well as by a slope sign of overlapping contours.

At the frequency of a cyclic transition (for example, 1-0' in the scheme of pumping from |1> level, Fig. 4), one observes a growth of the absorption, $S(F_m)$, due to the absence of pumping on this transition. At some frequencies between (1-0') – transition and adjacent (1-1') – one, a slope of the (1-0') – contour has the opposite sign, thus reducing, probably, the efficiency of FM-AM noise conversion. Finally, despite the lesser probability of transition (2:5), a cyclic transition gives a great quantity of re-emitted photons, thus resulting in "zeroing" of the total absorption *change* in the multi-level atomic system at some laser's frequency and therefore "zeroing" the FM-AM conversion noise. Similar effect has been observed and explained on Zeeman structure in [12].

"Zeroing"- effect of the FM-AM conversion noise is explained for different signals also in [13].

C. Atomic Vapour Discriminator's parameters. SNR value. Laser's frequency stabilization.

The measured SNR and figure-of-merit, M, values of discriminator operating with pumping on scheme $|1>-^2P_{3/2}$ presented in Fig. 6.

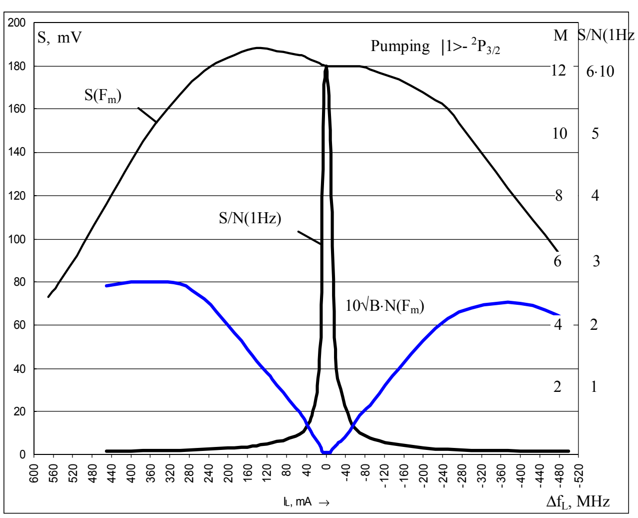

Figure 6. Dependences of DROR signal amplitude, $S(F_m)$, noise, $N(F_m)$, and SNR value of the ^{87}Rb vapour discriminator on laser frequency detuning, Δf_L. Pumping scheme: $|1> - ^2P_{3/2}$.

The achieved parameters of AD at the point of N_{min} for the case of pumping from the |1> level: SNR/Hz$^{1/2}$ = 8000, W = 504 Hz; the figure of merit M=16 that according to $\sigma_y(\tau) \sim 1.8{\cdot}10^{-12}{\cdot}\tau^{-1/2}$. The dependence of SNR value on Δf_L is very critical (Fig. 6). For laser's frequency detuning of < 10 MHz from the point of the AD's minimum noise (< 4 μA for the current) the SNR value is reduced by ~ 3 times. Therefore one should stabilize a laser's frequency using the ultimately narrow contour.

In known foreign developments of RFS with laser pumping a laser's frequency is stabilized using a narrow contour of the saturated absorption line in the auxiliary cell with ^{87}Rb vapour. It is, however, related to the significant technical device's complication because it requires gas-cell's temperature selection and stabilization, stable constant magnetic field, certain optics for laser's ray transit, its intensity optimization, etc. The laser's frequency noise is surmounted using such techniques as, for example, transmission of a laser ray through operating cell and auxiliary one (without a buffer gas) simultaneously and comparison of the noise levels as well as technique for FM noise suppression.

It seems to be logical not to surmount the laser's noise (with great complications, but without a noticeable success), but to operate at those conditions when there is no such a noise. For active stabilization of laser's frequency such a signal was used as that of atomic beam fluorescence (in the ABT) on (1-1') – hyperfine transition which is somewhat higher by frequency than the point where N_{min} is observed for the gas-cell AD (for pumping on $|1> - ^2P_{3/2}$ transition. A small frequency difference between a position of maximum of the atomic beam's fluorescence line on (1-1') – transition and N_{min} point was compensated due to Doppler effect. In so doing, the laser beam, using a semi-opaque mirror (or a fiber-optic collector), was put at the same time to gas-cell AD and ABT pumping zone – towards to the atomic beam at an angle exceeding 90^0 by 3-4^0. In the case of pumping from |2> level this angle will be less than 90^0. The technique for laser's frequency stabilization was successfully realized by us – the laser is functioning for a long (non-restricted) time at the point of minimum noise. The frequency standard's frequency-lock loop was closed. The confinement at the point of minimum noise (Δf_L^0) was checked against a minimum level of AD's output signal at f_m^L frequency, $S(f_m^L)$.

However, the atomic beam tube should, in principle, be excluded as a reference for laser's frequency stabilization, although it is possible to manufacture a mini-ABT ("a pencil" type) containing an atomic beam source and one optical chamber only.

It is interesting to decide a problem of possible using a dependence between signal's component at the AD's output and laser's frequency, $S(f_m^L)$, for laser frequency autonomous stabilization.

The next problem is to measure stability and light shifts of RFS breadboard and to find conditions for coinciding a laser's frequency corresponding to the minimum AD's light shift with a region of minimum-noise point (noise conversion).

IV. CONCLUSION

In order to realize a high-stability onboard frequency standard, a breadboard of Rb vapour discriminator with laser pumping is experimentally investigated.

The role of buffer gases and optical pumping is shown as regards the absorption line's generation for two pumping schemes: |2> - $^2P_{3/2}$ and |1> - $^2P_{3/2}$.

The course of AD's FM-AM noise conversion on the absorption contour is studied depending on laser's frequency detuning at low (F_m) and high (f_m^L) frequencies. It is shown that an operating point (Δf_L^0) – laser's frequency – exists at which the DROR signal has a special feature and the noise at low and high frequencies tends to minimum value. These points when pumping from |2> or |1> levels do not coincide with the peak of the corresponding absorption line and are located near the non-shifted (2-2') [from side of cyclic (2-3')] and (1-1') [from side of cyclic (1-0')] transitions respectively. The appropriate detuning values, Δf_L^0, were measured. The role of cyclic transitions is emphasized.

The dependence of the SNR value on laser frequency detuning is very sharp. The maximum SNR value is observed for laser detuning, Δf_L^0, corresponding to the point of minimum FM-AM conversion noise.

Such a task is solved as pinpointing conditions (laser's frequency, optimal pumping scheme) for obtaining the maximum figure of merit (SNR/W) in the presence of FM-AM noise conversion as the strongest source of RFS frequency instability.

The technique is proposed and realized for stabilizing a laser's frequency at the point of minimum FM-AM conversion noise using the resonance of atomic beam's fluorescence at which the difference in frequencies "absorption-emission" is compensated due to Doppler effect.

In the subsequent study, we suggest to optimize the physical package's parameters (cell, T, I_L) for making coincident laser's frequency corresponding to the minimum noise, Δf_L^0, with that of minimum light shift.

The possibility is shown for realizing a combined Rb frequency standard including two discriminators with laser pumping using a single laser: AD-ABT and AD-gas-cell.

ACKNOWLEDGMENT

We would like to acknowledge Dr. G. Mileti (LTF), Dr. J. Delporte (CNES) and Dr. E. N. Pestov (SPE) for supporting this work and helpful discussions.

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This work was supported by the INTAS-CNES Project no. 06-1000024-9321.