“Zeroing” of Magnetic Resonance signals and Amplitude Noises caused by frequency emission fluctuations when Pumping atoms with D_2 - line in Magnetometers and gas-cell frequency Standards

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***Abstract* – Based on experimental investigations, a role of D_2 - line’s cyclic transitions is shown in occurrence of “zeroing” signals and noise (AAN, FM-AM) and “zeroing” points displacement in cells with wall-coating when using lamp pumping. Such a phenomenon is considered as a behaviour of $S_z^{(0)}$ and $S_x^{(0)}$ signals in the Zeeman’s structure of the hyperfine F=I+J state for various alkali atoms (^{133}Cs, ^{87}Rb, ^{39}K, ^{41}K).**

It is shown, in particular, that FM-AM conversion disappears and SNR increase at the point of zeroing the first derivative of resonance signal.

It is proposed to use a zeroing point for laser’s frequency stabilization as well as for contactless measurement and stabilization of temperature as regards the operating gas itself in the absorption cell.

I. INTRODUCTION

The calculations show that the application of a laser diode for pumping can increase by an order a frequency stability of frequency standards based on absorbing cell with buffer gas mix, (Ar+Ne,..). However, it hasn’t been possible up to now to realize the advantages of laser pumping over the lamp one to the full extent due to additional amplitude noise (AAN). This noise arises when converting the frequency fluctuations (FM) of laser emission into the amplitude modulation (AM) on the optical absorption contour. This FM-AM conversion restricts significantly the signal-to-noise ratio (SNR) as well as the stability of a frequency standard.

In recent works [1,2], when observing a signal of the hyperfine “0-0” transition in the ^{87}Rb cell with buffer gases versus the change of a narrow-band D_2 - laser emission frequency, a point of the laser frequency was found at which the AAN noise decreased practically to the zero. As a result, the SNR value increased by more than an order [2,3]. In [1,2] and similar works, however, the physical nature of AAN decreasing to zero is not explained.

It should be noted that as early as in 1966 one observed the effect of zeroing of $S_{z,2}^{(0)}$ itself a signal in Cs atoms’ Zeeman transitions’ system within cells with buffer gas in lamp pumping with the wide D_2 - line [4] and then also in cells with ^{85}Rb and ^{87}Rb isotopes [5]. The effect manifested itself not only in zeroing $S_{z,2}^{(0)}$ - signal, but also in the inversion of atomic magnetization ($+M_z \rightarrow -M_z$) in the vicinity of the zeroing point when changing the buffer gas (He, Ar,…) pressure. The basis for this effect was the process of populations’ transformation in the $^2P_{3/2}$ state due to collisions of Cs (or Rb) atoms with those of buffer gas.

At the beginning of 70s, the author also observed “zeroing”, but for $S_x^{(0)}$ - signal (coherence signal) in the Cs self-oscillating magnetometer using a cell with paraffin coating and pumping ^{133}Cs atoms with two (D_1+D_2) - lines. The obtained $S_x^{(0)}$ signal zeroing was distinct from known other ones and could not be early explained for a some time since there were no collisional processes in the excited $^2P_{3/2}$ - state in the cells with coating. This waked us to conduct the considerable experimental investigations of S_z - and S_x - signals’ “zeroing” effect for lamp pumping with two (D_1+D_2) - and single D_2 - line in various alkali atoms. Later on, it was found that this effect manifested itself also in lowering the amplitude noise caused by the parasitic frequency modulation of $H_1 \cdot \cos(\omega_0 t)$ resonance field which takes part in the generation of the Zeeman resonance contour. Several specific features of the effect were presented in [6]. Figure 1 gives an example from [6] showing zeroing the $S_x^{(0)}$ - signal from the oscillating M_x - magnetization component in ^{87}Rb cell with wall-coating.

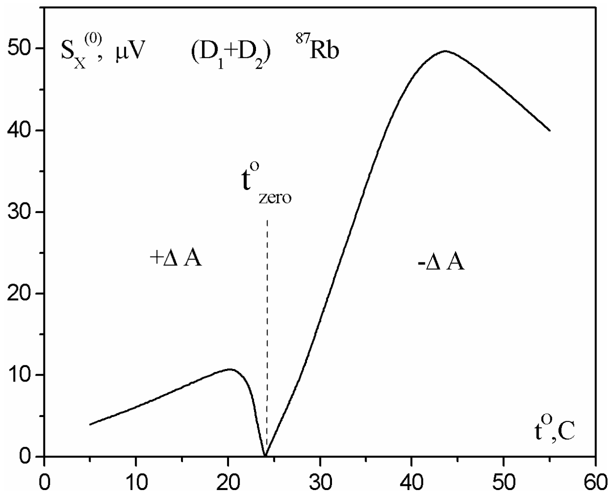

Figure 1. Pumpig ^{87}Rb atoms with two ($D_1 + D_2$) – lines.
Zeroing the $S_x^{(0)}$ coherence signal in cell with wall-coating.

"Zeroing" effects in various manifestations which are found on *Zeeman's* and *hyperfine* "0-0" *transitions* can be united in a special class of phenomena - "Zeroing resonance signals and zeroing FM-noise conversion".

This work, proceeding from the experimental investigations, shows a role of D_2 - line in the occurrence of "zeroing" effect as regards *signals* and noise (AAN, FM-AM), *displacement of zeroing points* in cells with wall-coating based on the example of behavior of $S_z^{(0)}$ and $S_x^{(0)}$ - signals of the Zeeman's structure in the hyperfine F = I+J state of various alkali atoms (^{133}Cs, ^{87}Rb, ^{39}K, ^{41}K). It is asserted that *the effect is caused by the action of D_2 - line's cyclic transitions*.

II. EXPERIMENT and RESULTS OBTAINED IN ZEROING THE ZEEMAN'S $S_x^{(0)}$ SIGNAL. PUMPING ^{87}Rb ATOMS with *TWO* (D_1+D_2) – LINES IN A CELL with WALL – COATING.

This subject should be considered to find a role of each optical line (D_1 and D_2) in the signals' "zeroing" effect.

The observation of the main $S_x^{(0)}$ signal, Fig.1, is performed using a known single-ray scheme in the Earth's field $H_0 \sim 0.515$ G. The light of (D_1+D_2) - lines (σ^+ polarization) was directed along the X axis and passed through the cylindrical ^{87}Rb cell with dimensions of 40 x 50 (∅, L). The field vector, $\mathbf{H_0}$, was in the ZX plane at $\alpha \sim 40^0$ angle relative to the X-optical axis. The resonance field, $H_{1,y}(t) = H_1 \cdot \cos(\omega_0 t + \varphi_0)$, was oriented along the Y axis. For observing other signals - first harmonic's signal, $S_x^{(1)}(\Omega)$, and that of the synchronous detector, S_{abs}, a small modulation field, $H_{2,z}(t) = H_2 \cdot \sin\Omega t$, was switched on along the H_0 constant field. $S_x^{(0)}(\omega_0)$ signal as well as $S_x^{(1)}(\Omega)$ and S_{abs} signals were subsequently taken at the specified temperature. When measuring a value of the main $S_x^{(0)}$ signal, the $H_2(t)$ modulation field is switched off. As a result, *three signals were observed*: first $S_x^{(0)}$ - at the Zeeman's transition's frequency $\omega_0 \sim 360$ kHz, than, at the same time, $S_x^{(1)}$ signal (at $\Omega/2\pi = 21$ Hz frequency) and S_{abs} signal showing a change in the light intensity, ΔA, when passing through the resonance.
Let us consider the results of the experiments.

- $S_x^{(0)}$ signal at the ω_0 frequency becomes equal to zero at the temperature $t^0_{zero} \sim 24^0$C. At the same point $S_x^{(1)}$ and S_{abs} - signals were also equal to zero ("Zeroing" signals).

- To the left of t^0_{zero} point the blooming of the cell takes place at the resonance, i.e. the contour of the emission line (+ΔA) is observed. To the right of t^0_{zero} point the darkening of the cell takes place at the resonance and the known absorption contour (-ΔA) is observed. At the t^0_{zero} point ΔA = | - ΔA|, $S_x^{(1)}$ and S_{abs} - signals are equal to zero.

- If the D_1 - filter is placed *after* the cell at the t^0_{zero} point, one will obtain all signals. It means that at this point the spin polarization exists, $M_z \neq 0$.

- The analysis of data in Fig.1 allowed us to make a conclusion that a reason for signals' zeroing when pumping atoms with two (D_1+D_2) - lines in cells with coating is a changing filtering of D_2 - lines's hyperfine components causing the "defect" in the recording channel [6].

III. ROLE OF OPTICAL D_1 – and D_2 – LINES IN ZEROING RESONANCE SIGNALS and ZEROING THE FM–AM CONVERSION

A. Procedures for conducting the experiment

*F*or the investigation one used a scheme for observing the $S_z^{(0)}$ signal of the M_z - magnetization component ($S_z^{(0)}$ is a signal of the change in the populations' difference and is similar to the signal in passive frequency standards). The $S_z^{(0)}$ signal had a higher SNR value compared to the $S_x^{(0)}$ signal and could be observed at the low temperature, $t^0 \sim 0^0$C for ^{133}Cs cell, $\sim 4^0$ for ^{87}Rb one and $\sim 10^0$ for ^{39,41}K cells. These cells with wall-coating were of dimensions of 40 x 50 and 40 x 70 (∅, L). The optical set-up axis coincided with the direction of the constant field, $H_0 = H_z$, and Z axis. For obtaining $S_z^{(0)}$ dependence the resonance amplitude modulated field $H_{1,y} = H_1 \cdot (1+m\sin\Omega t) \cdot \cos(\omega_0 t+\varphi_0)$ was used where m ~ 80 percent. The different modulation frequency ($\Omega/2\pi$ = 21 Hz and 80 Hz) was applied.

The sequence of observing $S_z^{(0)}$, $S_z^{(1)}$ and S_{abs} signals is similar to part II. First, the AM field was applied and the $S_z^{(0)}$ value was measured. Then AM was switched off and the modulating field, $H_{2,z}(t)$, along the Z axis is switched on for observing other signals, $S_z^{(1)}$ and S_{abs} .

Fig.2 and Fig.3 present the experimental dependencies of $S_z^{(0)}$ signals within t^0 range of (4÷48) ^{0}C for D_1 and D_2 - lines with different light intensities, $I_0(D_1)$ and $I_0(D_2)$, at the cell's input.

B. Results of experimental investigations

D_1 – line. *Absence of zeroing.*

Fig.2 presents the $S_{z,1}^{(0)}$ signal versus temperature for the various intensity of the pumping light, $I_{0,1}$. The dependences are of traditional nature without any specific featured. The change in the light at the resonance corresponds to the absorption contour, (-ΔA). As was shown by our subsequent studies, the absence of zeroing when D_1 - line's pumping is connected to the invariability of the hyperfine components' ratio in transmitting the light through a cell [7].

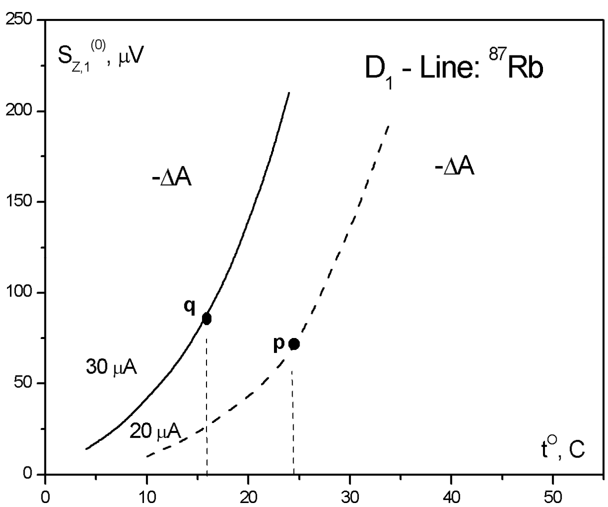

Figure 2. Pumpig ^{87}Rb atoms with D_1 – line. $S_{Z,1}^{(0)}$ signal of populations' difference (M_Z) vs temperature with different light intensities, $I_{0,1}$, at the cell's input. A value of the D_1 – line's photocurrent is $I_{0,1}$= 20, 30 μA.

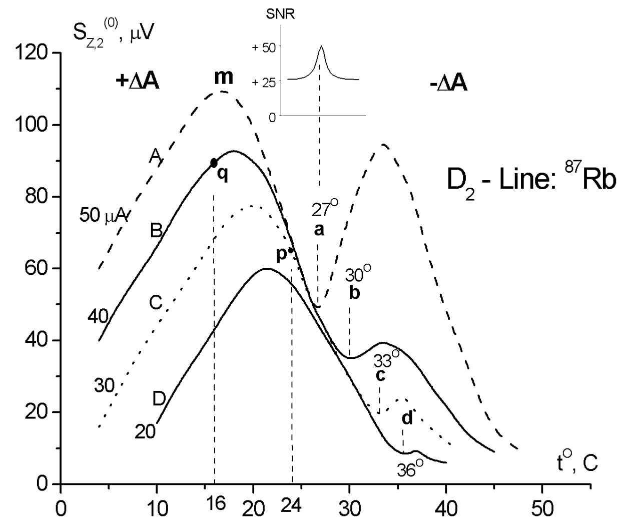

Figure 3. Pumpig ^{87}Rb atoms with D_2 – line. $S_{Z,2}^{(0)}$ signal vs temperature with different light intensities, $I_{0,2}$ (μA). **a**, **b**, **c**, **d** – points of zeroing a $S_{Z,2}^{(1)}$ -signal of modulation frequency 1st derivative and S_{abs} -signal of light changing at the resonance, ΔA.

D_2 – line. *Zeroing 1st derivative signal*, $S_{z,2}^{(1)}$, and *absorption signal*, S_{abs}.

Fig.3 presents a family $S_{z,2}^{(0)}$ - signal's dependences for various $I_0(D_2)$ values with marked minimum signals' points - a, b, c, d. These points are related to the temperatures, t^0_{zero} = 27, 30, 33, 36^{0}C, at which zeroing occurs for the $S_{z,2}^{(1)}$ - signal of the 1st derivative and S_{abs} - signal of light changing at the resonance (ΔA). In so doing, the $S_{z,2}^{(0)}$ - signal itself exists. To the left of t^0_{zero} points the emission contour (+ΔA) is observed, to the right of them - the absorption contour (-ΔA) takes place. At a, b, c, d - points the contours are mutually compensated. This results in zeroing FM-AM and AAN - emission noise.

For additional checking the zeroing points of $S_{z,2}^{(1)}$ and S_{abs}- signals the other variant of the frequency modulation was approbated similar to that used in frequency standards, $\nu_{0\text{-}0}+k\cdot\sin(\Omega t+\varphi_0)$. For this purpose, $H_2(t)$ field was switched off and the FM-resonance field, $H_{1,y} = H_1 \cdot \cos[\omega_0 t + k \cdot \sin(\Omega t+\varphi_0)]$, was applied to the spin system. As was expected, $S_{z,2}^{(1)}$ and S_{abs} - signals were equal to zero. The 2nd harmonics at 42 or 160 Hz were also equal to zero.

D_2 – line. SNR *increase at the points of zeroing* the FM-AM *conversion*.

At the "a" point, for example, Fig.3 a SNR value increased by ~ 2 times. This increase was not so large as in works [2,3] when the significant parasitic FM took place in the laser emission. In our experiments the lamp emission had no parasitic frequency modulation, therefor AAN only were eliminated caused by the FM disturbance as regards H_0 field and H_1 resonance field channel.

(D_1+D_2) – lines. $S_x^{(0)}$ and $S_z^{(0)}$ *signals zeroing.*

Using the data presented in Fig.2 and Fig.3, one can easily explain a $S_x^{(0)}$ signal's zeroing point in Fig.1. The spectral lamp practically used have the light intensities' ratio $D_1 : D_2 \sim 1{:}1{,}25$ (according to calculations, this ratio should be 1:2). For the specified lamp's regime, the intensities $I_{0,1}(D_1)$ = 20 µA and 30 µA (Fig.2) corresponded to intensities $I_{0,2}(D_2)$ = 30 and 40 µA (Fig.3). At the "p" point $S_{z,1}^{(0)}$-signal of the D_1 line ($I_{0,1}$ = 20 µA) and $S_{z,2}^{(0)}$ - signal of the D_2 - line ($I_{0,2}$ = 30 µA) became equal, but have different signs, -ΔA and +ΔA, respectively. As a result, when pumping with two (D_1+D_2)-lines, a zeroing point, t^0_{zero}~24^{0}C, arises, Fig.1. There is also the second "q" point to which $t^0_{zero} \sim 16^0$C corresponds.

Zeroing point's dynamics. Pumping with **D_2 – line** of *potassium isotopes*, ^{39}K and ^{41}K.

^{39}K and ^{41}K atoms' pumping is of special interest. It is related to specific features of the energy splitting ground $4^2S_{1/2}$ and excited $4^2P_{1/2,\ 3/2}$ levels. ^{39}K and ^{41}K isotopes have a nuclear spin I = 3/2, and their levels' structure coincides with that of ^{87}Rb. But the energy intervals between hyperfine levels in $^2S_{1/2}$ and $^2P_{1/2,\ 3/2}$ – states are lesser by more than the order than in ^{87}Rb (splitting between hyperfine levels in $^2P_{3/2}$ - state for ^{87}Rb is 267; 157; 72 MHz, whereas for ^{39}K – 21; 9.2; 3.2 MHz). $^2S_{1/2}$ state's splitting ($f_{0\text{-}0}$ ~ 0.461 GHz, ^{39}K) is also concealed under the Doppler contour.

Fig.4 presents a dependence between a zeroing point of ^{41}K atoms' $S_{z,2}^{(0)}$ - signal and $I_{0,2}$ light intensity (*zero signal's curve*). (The cell is coated with the deuterated polyethylene).

The dependence shows a specific behavior of ^{41}K pumping. One of specific features is that $S_{z,2}^{(0)}$ (and $S_{x,2}^{(0)}$) signal's zeroing occurs already when pumping with a *single* D_2 -line, whereas zeroing the same signals in ^{87}Rb-cells arises when pumping with *two* (D_1+D_2) - lines. Within a region restricted by t^0_{zero} ($I_{0,2}$) curve one observes $S_z^{(0)}$ (and $S_x^{(0)}$) signals with the cell's clarification (+ΔA) for the resonance at F=2 level; beyond the curve's region we have absorption signals, (-ΔA).

At the F = 1 level the absorption signals (-ΔA) are *only* observed.

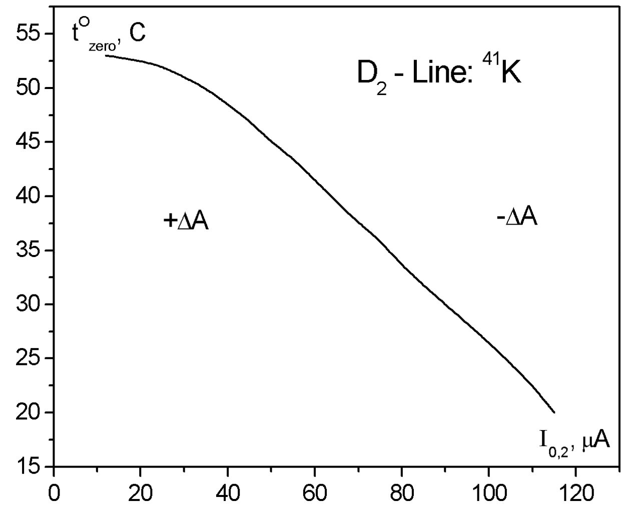

Figure 4. Pumping ^{41}K atoms with D_2 – line. *Zero signal's curve*, $S_{z,2}^{(0)}$ and $S_{x,2}^{(0)}$.

IV. ANALYSIS OF INVESTIGATIONS' RESULTS FOR LAMP PUMPING with D_1– and D_2 – LINES IN WALL–COATING CELLS. *CONCLUSIONS.*

- The physical nature of "zeroing" effect for various signals, AAN zeroing and FM-AM conversion lies in the joint action of cyclic transition and "thick layer" effect. The role of a cyclic transition is best seen in the case of polarization pumping with σ^+ (or σ^-) light when the edge transition (|F=2, m_F=2>→|F'=3, $m_{F'}$=3>) is involved which has the most probability compared to others.

- To the right of "m" point (A curve, Fig.3), the manifestation of the "thick layer" effect is enhanced, thus resulting in a decrease in the cell's transparency (+ΔA) depending on temperature. At the "a" point cell's transparency (+ΔA) and absorption (-ΔA) level become identical, ΔA=0. As a result, one observes disappearance of emission FM-AM conversion and increase in SNR at this "a" point.

- The "m" point of the signal maximum within a cell's transparency region (+ΔA) can serve a practical criterion for evaluating a "thick layer" with the specified light intensity.

- Zeroing points displace due to various relaxation processes (buffer gases' pressure and kind, temperature, resonance field value ($H_{1,\ y}$), and other factors).

- When pumping with D_2 - line using a lamp, the intensity of found processes depends on a changing ratio of hyperfine components [7] in the absorption cell (and *in the lamp* [6]).

V. LASER PUMPING with D_2 – LINE IN CELLS with BUFFER GASES

Based on results obtained for Zeeman's transitions, one can now appreciate a reason for occurring points of AAN zeroing and significant SNR increase in [3] when pumping with D_2 - line.

- The occurrence of AAN zeroing points when observing a hyperfine "0-0" resonance in ^{87}Rb with buffer gases [3] is also related to the impact of cyclic transitions (|F = 2> → |F' = 3> or |F = 1>→|F' = 0>). In this case, a laser's frequency ν_L corresponding to the zeroing point should not coincide with the cyclic transition's frequency (according to part IV). ν_L frequency and, consequently, AAN zeroing points will be placed between hyperfine optical transitions, one of which is a cyclic one. This foundation is confirmed in [3].

- The results of our investigations on pumping with D_2 - line using a lamp allow to expect a displacement of AAN zeroing point depending on laser's line intensity and width ($\Delta\nu_L$), buffer gas pressure and H_1 field value, and this is confirmed in a number of works, for example, [8].

VI. ENGINEERING APPLICATION OF INVESTIGATION RESULTS

For each pumping variant, for example |F=1>→ $^2P_{3/2}$ (I = 3/2), this point is a single one. It can be used for the stabilization of a frequency laser [2,3] or for the contactless measurement and temperature stabilization of operating gas itself in an absorption cell [6].

ACKNOWLEDGMENT

Author would like to acknowledge Dr. A. Besedina (RIRT) and senior researcher D. Pestov for helpful discussions and supporting this work.

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