ANALYSIS OF PASSIVE ATOMIC FREQUENCY STANDARD STABILITY

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ABSTRACT

The improvement of various technical systems using atomic frequency standards dictates the increase of these devices' stability. This paper discusses techniques for optimal selection of passive frequency standard parameters which could provide a realization of the best frequency stability over a broad range of measurement interval. Investigated also is an effect of various frequency standard parameters' fluctuations on stability of those.
Keywords : frequency standards, frequency stability, optimization methods.

1. INTRODUCTION

The practice of using passive frequency standards (AFS) in various systems (for example, in satellite navigation systems) shows a necessity for further improving both short-term and long-term frequency stability of those devices. For defining ways to this improvement, the techniques should be required for optimal selecting values of parameters on which a stability of the AFS depends. The available references only reflect specific problems of such a selection. In addition, sometimes just the opposite points of view arise. The other aspect of problem related to realization of the best passive AFS frequency stability contains in restrictions caused by a technique adopted now for processing an error signal. This technique is based on phase modulation of the microwave signal probing a working substance with a subsequent synchronous detection at the modulation frequency for the generating a signal controlling over a frequency of the reference crystal oscillator (QO). Therefore the problems on optimal selection of parameters for cesium and rubidium AFS and estimate of effect of various fluctuation processes on frequency stability are the subject of this paper.

2. OPTIMIZATION CRITERION

For the parametric optimization of a technical device, an optimization criterion should be available which contains as follows : information on quality with which the device executes its functions; mathematical device model defining the dependences of the optimization criterion on values of internal device parameters, and formalized algorithm for finding optimal values of these parameters which provide the greatest or the smallest value of the optimization criterion using restrictions previously defined for possible values of optimization parameters. Therefore let us consider at first a generalized mathematical model of the passive AFS.

2.1 Mathematical Model of the Passive AFS

Fig. 1 represents an equivalent block diagram of the passive AFS as an automatic frequency lock system. Shown are transfer functions of its units in the linear approximation and random disturbances as well. It was assumed in this case that all these disturbances are statistically independent. The main fluctuations acting in the systems are as follows : intrinsic frequency fluctuations of the QO and non-multiple frequency transformer, output signal fluctuations of the atomic discriminator and frequency fluctuations of the clock atomic transition of the atomic discriminator. According to the data of experimental investigations [1], the spectral densities (SPD) of crystal oscillator (QO) frequency fluctuations, output signal of the atomic discriminator (AD) and frequency of non-multiple frequency transformer (NFT) take the following form :

$$W_{QO}(\Omega) = \frac{A_{QO}}{\Omega^2} + \frac{B_{QO}}{\Omega} + C_{QO} \quad (1)$$

$$W_{AD}(\Omega) = C_{AD} \quad (2)$$

$$W_N(\Omega) = A_N + B_N\Omega + C_N\Omega^2 \quad (3)$$

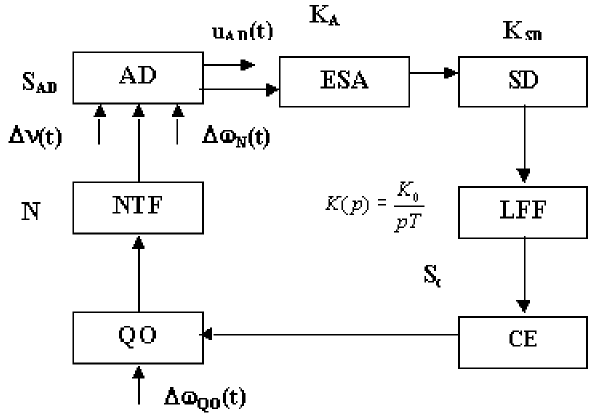

Fig. 1. Equivalent block diagram of the passive AFS as an automatic control system. AD - atomic discriminator, ESA - error signal amplifier, SD - synchronous detector, LFF - low frequency filter, CE - control element, QO - crystal oscillator, NTF - non-multiple frequency transformer.

Frequency fluctuations of the clock atomic transition are defined by fluctuations of parameters on which this frequency depends. Therefore SPD of frequency fluctuations for the clock atomic transition frequency takes following form [2]:

$$W_\nu(\Omega) = \sum_i D_i^2 W_i(\Omega) = \sum_i D_i^2\left(\frac{A_i}{\Omega^{\alpha_i}} + C_i\right) = \sum_i \left(\frac{A_i}{\Omega^{\alpha_i}} + C_i\right), \quad (4)$$

where W_i - SPD of fluctuations of the i-th parameter causing a frequency shift of the clock atomic transition and $D_i = \partial\nu/\partial P_i$ - respective differential parametric frequency shift, ν - clock atomic transition frequency, P_i- i-th parameter value.

The most informative analytical measure for the frequency instability of AFS is a fractional root-mean-square frequency variation (Allan variance) :

$$\sigma(\tau) = \frac{\sqrt{\left\langle\left(\langle\omega\rangle_{t_{k+1},\tau} - \langle\omega\rangle_{t_k,\tau}\right)^2\right\rangle}}{\omega_0} = \frac{1}{\omega_0}\sqrt{\frac{8}{\pi}\int_0^\infty W(\Omega)\frac{\sin^4\frac{\Omega\tau}{2}}{(\Omega\tau)^2}d\Omega}, \quad (5)$$

where $\langle\omega\rangle_{ti,\tau}$ - i -th individual sample of the AFS output frequency measured over τ interval, ω_0 - nominal value of the AFS output frequency, $W(\Omega)$ - SPD of QO frequency fluctuations within the closed frequency lock loop of AFS.
$W(\Omega)$ quantity consists of four parts :

$W(\Omega) = |G_{QO}(i\Omega)|^2 W_{QO}(\Omega) + |G_{AD}(i\Omega)|^2 W_{AD}(\Omega) +$

$+ |G_N(i\Omega)|^2 W_N(\Omega) + |G_\nu(i\Omega)|^2 W_\nu(\Omega)$

where, $G_{QO}(i\Omega)$, $G_{AD}(i\Omega)$, $G_N(i\Omega)$, $G_\nu(i\Omega)$- transfer coefficients for the closed system from $\Delta\omega_{QO}(t)$, $u_{AD}(t)$, $\Delta\omega_N(t)$, $\Delta\nu(t)$ disturbance application points to the output.

When substituting $W(\Omega)$ along with evident expressions for $G_i(i\Omega)$ in (5), one can obtain an expression for $\sigma(\tau)$ which is too cumbersome to give here [1]. The instability of the AFS output frequency within an area of small measurement time intervals, τ, is defined by intrinsic frequency instability of the crystal oscillator and by $F = S_{AD} / \sqrt{W_{AD}}$. This quantity is generally named "a figure of merit" of atomic discriminator. Within an area of τ large values, the AFS frequency instability is defined by differential parametric frequency shifts of the clock atomic transition of the atomic discriminator. In addition, an Allan variance depends on the cut-off frequency, Ω_0, of the frequency lock loop and QO, AD, NFT fluctuation characteristics. Therefore, optimization objects are frequency lock loop (FLL) and atomic discriminator, and the generalized mathematical model of AFS should include mathematical model of the atomic discriminator and mathematical model of FLL which defines Allan variance dependence of AFS output frequency on parameters of fluctuation processes, parameters of the atomic discriminator and FLL parameters.

2.2. Generalized AFS Figure of Merit

A common demand for AFS accuracy parameters imposed by users is a provision for Allan variance specified values over a certain measurement time interval $[\tau_1,\tau_2]$. Therefore one can use a mean Allan variance as a criterion for complex optimization of AFS over this measurement time interval :

$$\Xi = \frac{1}{\tau_2 - \tau_1} \int_{\tau_1}^{\tau_2} \sigma(\tau, F, D_1, D_2, ..., \Omega_0) d\tau , \quad (6)$$

where F - figure of merit of the atomic discriminator, D_i - i-th differential parametric frequency shift of the clock atomic transition of the AD, Ω_0 - FLL cut-off frequency. The $[\tau_1,\tau_2]$ interval is usually quite broad, so, to level off weights of short-term and long-term frequency instability, it is advisable to use log-log scale and define a generalized figure of merit (GFM) of AFS as the criterion for AFS complex optimization expressed by :

$$Z(\tau_1, \tau_2) = \frac{1}{\lg\left(\tau_1 / \tau_2\right)} \int_{\lg \tau_1}^{\lg \tau_2} \lg[\sigma(\tau)] d(\lg \tau) \quad (7)$$

3. COMPLEX OPTIMIZATION OF CESIUM AFS

For complex optimization of a cesium beam AFS, a computer procedure was developed for searching the greatest value of the generalized AFS figure of merit over a hyperspace of AFS parameters and FLL cut-off frequency. The mathematical atomic beam tube (ABT) model [2] comprised a dependence of ABT figure of merit and differential parametric frequency shifts on following parameters of ABT with dipole selecting systems : ψ_1, ψ_2 – slope angles of beam source and detector against the ABT optical axis; l_{m1}, l_{m2} – lengths of selecting magnets; l_s, l_d – distances from beam source and detector to the respective selecting magnet; S_ϕ, f – widths of the forming aperture at the input of selecting magnet and detector ribbon; R_{12} – microwave excitation parameter; Δ - deviation of the microwave field low-frequency switching. The dependences of the ABT figure of merit on this values takes the form of unimodal extreme curves. In the course of computations the experimental values of SPD of beam source temperature, microwave excitation power and C-field fluctuations were used.

Depending on sign combinations of ψ_1, ψ_2 and signs of magnetic field gradients, $\partial H_{0A}/\partial z$ and $\partial H_{0B}/\partial z$, in selecting magnets there are possible 16 types of the geometrical dipole optics, of which only four are independent. Fig. 2 shows the frequency stability for those variants. As is seen from plots given in Fig 2, the first variant is more preferable

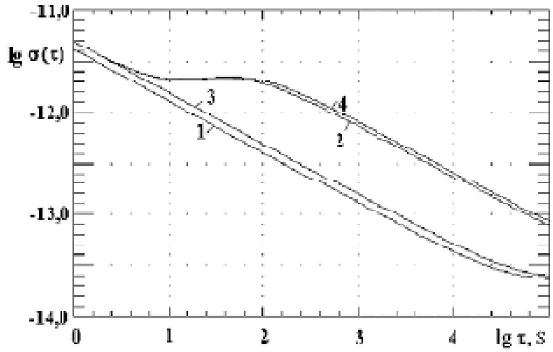

Fig. 2.

4. COMPLEX OPTIMIZATION OF A RUBIDIUM GAS CELL FREQUENCY STANDARD

4.1 Complex optimization

A mathematical model of the gas cell atomic discriminator (AD) was developed based on the microscopic theory of the double radio-optical resonance [3]; it comprised dependences of figure of merit , differential light shift (DLS) and differential temperature shift (DTS) of the clock atomic transition frequency on following AD parameters : L_c ,T_c – length and temperature of the gas cell and P_c – buffer mix pressure in it; L_F , T_F – length and temperature of the isotopic filter and P_F – buffer gas pressure in it; J_{in} – pumping light intensity at the filter input; R_{12} – microwave excitation parameter and Δ - deviation of microwave field low-frequency switching. Therefore the discriminator parameters to be optimized are P_c, T_c , P_F , T_F , J_{in}, , R_{12} , and Δ. Fig. 3 represents plots for frequency stability of this AFS with H_{111} gas cell cavity.

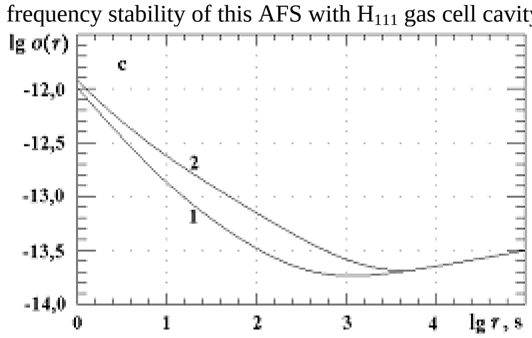

Fig. 3

4.2 Selection of Pumping Light Intensity Value

When theoretically analyzing optimal modes of the gas cell AD, it is usually adopted to use a dimensionless optical pumping rate $Q = (\Gamma_1 + \Gamma_2)/2\gamma$, where Γ_1 и Γ_2 – pumping rates from different hyperfine levels of the ground state, γ - longitudinal relaxation rate. There are a great spread of optimal Q values proposed by authors of references dedicated to this problem. In [4] this value is adopted equal to 4.5. In [5] optimal Q value is estimated as about 1.0, thus agreeing with our data, but it is proposed there to use a "superslow" pumping mode with even much less values of the pumping rate. In authors' point of view, such a mode results in increase of the long-term frequency stability due to a decrease in the light frequency shift. This frequency stability is, however, not defined by the light frequency shift, $\Delta\nu_{op}$, but by the differential light shift , $\partial\Delta\nu_{op}/\partial J$. Moreover, near the optimal mode a dependence of the light shift is essentially non-linear and zero values of light shift and DLS are achieved in significantly different AD modes. The optimal value of the light intensity providing the largest value of the generalized AFS figure of merit is of enough large value. The selection of intensity being less then this value does not result in an increase in long-term frequency stability, but can give a decrease in a short-term and medium-term stability. Such a situation is shown in Fig. 3 where calculated plots of frequency stability are given for optimal light intensity (curve 1) and intensity four times decreased (curve 2).

5. TRANSFORMATION OF MICROWAVE FIELD PHASE FLUCTUATIONS AND SHORT-TERM FREQUENCY STABILITY OF A PASSIVE AFS

The transformation of fluctuations in a beam tube AFS is investigated in [6]. In a case of the gas cell AD, it is impossible to obtain accurate expressions for fluctuation transformation coefficients. But, when a period of the microwave field low-frequency modulation is large compared to AD dynamic time constants, one can use a quasi-stationary approach. In the frameworks of this approximation, when a sine (or other smooth) form of the modulation signal takes place, a signal from AD output can be represented as a sum of modulation harmonics :

$$A(t) = A_0(P,J,\delta) + \sum_{k=1}^{\infty}\left[A_k(P,J,\delta)\sin k\Omega_M t + B_k(P,J,\delta)\cos k\Omega_M t\right] \quad (8)$$

where P – microwave field power, J –pumping light intensity, Ω_M – angular modulation frequency, δ - detuning of microwave field frequency. Quantities P, J can be represented as a sum of determined components, $\bar{P}$ и $\bar{J}$ and small fluctuations $\pi(t)$ and $\iota(t)$, respectively. Considering these fluctuations statistically independent, one can, using quasi-classical approximation, represent A(t) as the expansion in terms of small fluctuations' powers, $\delta(t)$, $\pi(t)$, $\iota(t)$:

$$A(t) = C_0 + \sum_{k=1}^{\infty} C_k\cos(k\Omega_M t + \varphi_k) + S_0\delta(t) + \delta(t)\sum_{k=1}^{\infty} S_k\cos(k\Omega_M t + \psi_k) +$$
$$+ \Pi_0\pi(t) + \pi(t)\sum_{k=1}^{\infty}\Pi_k\cos(\Omega_M t + \vartheta_k) + \Upsilon_0\iota(t) + \iota(t)\sum \Upsilon_k\cos(k\Omega_M t + \xi_k)$$

where

$$C_0 = A_0(\bar{P},\bar{J},0);\ S_0 = \frac{\partial A_0(\bar{P},\bar{J},\delta)}{\partial\delta}\Big|_{\delta=0};\ \Pi_0 = \frac{\partial A(P,\bar{J},0)}{\partial P}\Big|_{P=\bar{P}},$$

$$\Upsilon_0 = \frac{\partial A(\bar{P},J,0)}{\partial J}\Big|_{J=\bar{J}};\ S_k = \sqrt{\left[\frac{\partial A_k(\bar{P},\bar{J},\delta)}{\partial\delta}\right]^2_{\delta=0} + \left[\frac{\partial B_k(\bar{P},\bar{J},\delta)}{\partial\delta}\right]^2_{\delta=0}}$$

$$\Pi_k = \sqrt{\left[\frac{\partial A_k(P,\bar{J},0)}{\partial P}\right]^2_{P=\bar{P}} + \left[\frac{\partial B_k(P,\bar{J},0)}{\partial P}\right]^2_{P=\bar{P}}};$$

$$\Upsilon_k = \sqrt{\left[\frac{\partial A_k(\bar{P},J,0)}{\partial J}\right]^2_{J=\bar{J}} + \left[\frac{\partial B_k(\bar{P},J,0)}{\partial J}\right]^2_{J=\bar{J}}};$$

$$\varphi_k = arctg\frac{A_k(\bar{P},\bar{J},0)}{B_k(\bar{P},\bar{J},0)};\ \psi_k = arctg\frac{\dfrac{\partial A_k(\bar{P},\bar{J},\delta)}{\partial\delta}\Big|_{\delta=0}}{\dfrac{\partial B_k(\bar{P},\bar{J},\delta)}{\partial\delta}\Big|_{\delta=0}}$$

$$\vartheta_k = arctg\frac{\dfrac{\partial A_k(P,\bar{J},0)}{\partial P}\Big|_{P=\bar{P}}}{\dfrac{\partial B_k(P,\bar{J},0)}{\partial P}\Big|_{P=\bar{P}}};\ \xi_k = arctg\frac{\dfrac{\partial A_k(\bar{P},J,0)}{\partial J}\Big|_{J=\bar{J}}}{\dfrac{\partial B_k(\bar{P},J,0)}{\partial J}\Big|_{J=\bar{J}}}$$

After synchronous detection with the selective amplification we obtain a following signal to control over QO frequency :

$$U_{out}(t) = K\begin{Bmatrix} C_1\left[\cos(2\Omega_M t + \varphi_1 + \Phi) + \cos(\varphi_1 - \Phi)\right] + 2S_0\delta(t)\cos(\Omega_M t + \Phi) + \\ + \delta(t)S_1\left[\cos(2\Omega_M t + \psi_1 + \Phi) + \cos(\psi_1 - \Phi)\right] + \\ + 2\Pi_0\pi(t)\cos(\Omega_M t + \Phi) + \pi(t)\Pi_1\left[\cos(2\Omega_M t + \vartheta_1 + \Phi) + \cos(\vartheta_1 - \Phi)\right] + \\ + 2\Upsilon_0\iota(t)\cos(\Omega_M t + \xi_1 + \Phi) + \iota(t)\Upsilon_1\left[\cos(2\Omega_M t + \xi_1 + \Phi) + \cos(\xi_1 - \Phi)\right] \end{Bmatrix}$$

where $K = K_aK_{SD}$, K_a – gain of selecting amplifier, K_{SD} – transfer ratio of synchronous detector. $C_1 = 0$ in the operating mode. Then SPD of the synchronous detector output signal fluctuations are equal:

$$S_D(\Omega) = K^2\begin{Bmatrix} S_1^2 S_\delta(\Omega)\cos^2(\psi_1 - \Phi) + S_0^2\left[S_\delta(\Omega - \Omega_M) + S_\delta(\Omega + \Omega_M)\right] + \\ + \frac{1}{4}S_1\left[S_\delta(\Omega - 2\Omega_M) + S_\delta(\Omega + 2\Omega_M)\right] + \\ + \frac{1}{4}\Pi_1^2\left[S_\pi(\Omega - 2\Omega_M) + S_\pi(\Omega + 2\Omega_M)\right] + \\ + \Upsilon_1^2 S_\iota(\Omega)\cos^2(\xi_1 - \Phi) + \frac{1}{4}\Upsilon_1^2\left[S_\iota(\Omega + 2\Omega_M) + S_\iota(\Omega - 2\Omega_M)\right] + \\ + \Pi_0^2\left[S_\pi(\Omega - \Omega_M) + S_\pi(\Omega + \Omega_M)\right] + \Upsilon_0^2\left[S_\iota(\Omega - \Omega_M) + S_\iota(\Omega + \Omega_M)\right] \end{Bmatrix}$$

As far as in the operating mode (when $\bar{\delta}$ = 0) $C_1 = 0$ for any value of P and J, then $\Pi_1 = 0$ and $\Upsilon_1 = 0$. On the other side, $C_0(P,J,\delta)$ is an even function of detuning, δ, therefore $S_0 = 0$. The optimal AD tuning is correspondent to a mode of saturation by microwave field power and pumping light intensity, during which a signal of the double radio-optical resonance does not practically depend on these quantities. It enables one to put Π_0 and Υ_0 values equal to zero. In order to realize a maximum operating efficiency for FLL system, a phase shift of the reference synchronous detector's signal is being selected under the condition $\Phi = \psi_1$. Taking into account assumption made, the above expression is transformed to :

$$S_D(\Omega) = K^2\left\{S_1^2\left[S_\delta(\Omega) + \frac{1}{4}S_\delta(\Omega - 2\Omega_M) + \frac{1}{4}S_\delta(\Omega + 2\Omega_M)\right]\right\}$$

Thus, the fluctuations; SPD for a control signal of QO has two components – component proportional to SPD of own fluctuations of the microwave field frequency and component describing a fluctuations' transfer from the Fourier-frequencies vicinity (equal to the double modulation frequency) to the zero Fourier-frequency of the control signal. As far as a cut-off frequency of the FLL system is small, the QO frequency fluctuations at $2\Omega_M$ are not filtered by the FLL system, and this component takes a part of the additional fluctuation source resulting in degradation of the short-term AFS stability which is mainly defined in this case by the own QO frequency stability. The effective way for neutralizing this effect is to use a low-frequency square modulation of the microwave field with quasi-stationary samples of the error signal which beginning is shifted by a duration of AD transients, ϑ, against the time instant of frequency switching. In this case, an error signal from the AD output is :

$$A(t) = A(\delta + \Delta)\Pi[t, nT + \theta, (2n+1)T/2] + A(\delta - \Delta)\Pi[t, (2n+1)T/2 + \theta, (n+1)T]$$

where $\Pi(t,\tau_1,\tau_2) = \delta_0(t - \tau_1) - \delta_0(t - \tau_2)$, T – modulation period, Δ - deviation of microwave field frequency, and $\delta_0(t - \tau)$ – unit function. Using an expansion of A(t) in terms of powers of a small frequency detuning, δ, near $\delta = 0$, we obtain :

$$A(t) = \{A(\Delta + \delta(t)S_+)\}\Pi[t, nT + \theta, (2n+1)T/2] + \{A(-\Delta + \delta(t)S_-)\}\Pi[t, (2n+1)T/2 + \theta, (n+1)T]$$

For a symmetrical line shape of atomic resonance $S_+ = S_- = S_{AD}$, $A(\Delta) = A(-\Delta)$. After synchronous detection of the variable signal part. using a reference signal of the square form, we obtain a following signal controlling the QO frequency :

$$U_{out}(t) = K_a K_{SD} S_{AD} \delta(t) \Pi[t, nT + \theta, (2n+1)T/2]$$

The expansion of this expression into the Fourier series gives

$$U_{out}(t) = K_a K_{SD} S_{AD} \delta(t) \left\{ (1-\vartheta) + \frac{2}{\pi} \sum_{n=1}^{\infty} \frac{(-1)^{n+1} \sin(n\pi\vartheta)}{n} \cos 2n\Omega_M t \right\}$$

where $\eta = 2\theta/T$, $\Omega = 2\pi/T$ – angular modulation frequency. SPD of frequency fluctuations of the output synchronous detector signal is :

$$S_D(\Omega) = K_s^2 \left\{ (1-\vartheta)^2 S_\delta(\Omega) + \frac{1}{\pi^2} \sum_{k=1}^{\infty} \frac{\sin^2 k\pi\vartheta}{k^2} [S_\delta(\Omega + 2k\Omega_M) + S_\delta(\Omega - 2k\Omega_M)] \right\}$$

where $K_s = K_a K_{SD} S_{AD}$, $S_\delta(\Omega)$ – SPD of microwave field frequency fluctuations. In this case, SPD of the additional noise generated by the spurious transformation of microwave field frequency fluctuations is equal to :

$$S_{add}(\Omega) = \frac{2N^2 S_{AD}^2 C_{QO}}{\pi^2} \sum_{k=1}^{\infty} \frac{\sin^2 k\pi\vartheta}{k^2} = N^2 S_{AD}^2 C_{QO} \vartheta (1-\vartheta)$$

This expression shows that the smaller is η, the smaller is an intensity of the additional noise. Decreasing in modulation frequency, one can in practice totally eliminate an effect of the spurious transformation of microwave field frequency fluctuations on short-term AFS frequency stability.

6. EFFECT OF CONSTANT MAGNETIC FIELD FLUCTUATIONS ON THE AFS FREQUENCY STABILITY

One of the main factors of the frequency instability are fluctuations of the constant magnetic field strength. The dependence of a hyperfine 0-0-transition in cesium and rubidium atoms on the value of the constant magnetic field is described as : $\nu = \nu_0 + \alpha H_0^2$ (8)

Magnetic field fluctuations are largely defined by power supply fluctuations. The SPD of fractional voltage fluctuations on the load is subject to the following law :

$S_U(\Omega) = A / \Omega^\gamma$,

where A (from 10^{-6} to 10^{-16}) – noise level, γ (from 1.2 to2.5) – exponent. Using this dependence as well as a linear dependence of the magnetic field strength on the power supply current, the square dependence (8) enables one to determine a frequency fluctuation SPD for the atomic transition through the autocorrelation of the noise action as

$S(\Omega) = B\, S_U(\Omega) \otimes S_U(\Omega)$

Where $B = 2\{\alpha A(nI_0/d)^2\}^2$,

I_0 – constant current value, d and n – diameter and number of turns of solenoid. For isolated conductor (n = 1) d – distance from conductor axis to the point of magnetic field generation in the plane perpendicular to the conductor axis. In a general case, it is impossible to obtain autoconvolution integrals with an arbitrary value of γ exponent. Therefore let us restrict ourselves by γ integer value. Then we obtain following expressions for SPD of atomic transition frequency fluctuations :

For $\gamma = 1$ $S(\Omega) = -(B/\Omega)\ln|\Omega/\Omega_1 - 1|$

For $\gamma = 2$ $S(\Omega) = B/\Omega^2(1/\Omega_1 - 1/(\Omega-\Omega_1) + (2/\Omega)\ln|(\Omega/\Omega_1) - 1|$

For $\gamma = 3$ $S(\Omega) = -B/\Omega^3 [3/\Omega(\Omega-\Omega_1) + 1/2(\Omega-\Omega_1)^2 - 3/(\Omega-\Omega_1) - 1/\Omega_1^2 - (6/\Omega^2)\ln|(\Omega/\Omega_1) - 1|$

Fig. 4 represents a frequency stability for the cesium AFS at the constant noise level, $A = 10^{-6}$, and three values of γ exponent. A constant current value, I_0 , is selected to be 25 mA with n = 5 and d = 2 cm, thus providing a strength of the constant magnetic C-field, H_0 = 79 mOe. The abruptest curve for frequency stability vs τ is observed in a case of the largest value of γ (curve 3 for $\gamma = 3$). All dependences represented in this figure with integer γ values are continuous and monotonic. Therefore, for γ of intermediate values with a decimal part, for example, 2.5, the curve takes an intermediate position between curves for $\gamma = 2$ and $\gamma = 3$. Frequency stability plots for the rubidium AFS is similar to those for the cesium AFS. One can see that a character of dependencies is retained, but a frequency instability is of a large value for all time measurement interval durations due to the larger value of α coefficient. The results of computations enable one to estimate a contribution to the passive AFS frequency stability caused by the solenoid power supply generating a constant magnetic field. So, for a stabilized power supply with a noise level of $A = 10^{-10}$ and $\gamma = 2$ exponent, a long-term frequency stability over a measurement time interval of 10^5 s is limited for cesium and rubidium AFS by a value of about $1 \cdot 10^{-14}$. With the same noise level, A, but for $\gamma = 2.5$, the frequency stability degrades to a value of $1 \cdot 10^{-12}$.

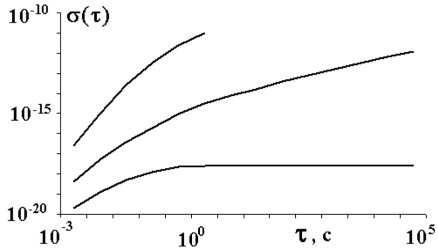

Fig. 4

7. CONCLUSIONS

The results represented in this paper show that the actually achievable values for passive AFS frequency stability are about $(2\text{-}4) \cdot 10^{-12}$ over 1 s and $1 \cdot 10^{-14}$ over 1 day. To realize such values, one should provide an optimal selection of AFS parameter values and take measures for neutralization of the spurious transformation of microwave field frequency fluctuations and for decreasing in constant magnetic field fluctuations.

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