7 TH EUROPEAN FREQUENCY AND TIME FORUM NEUCHÂTEL - 16 - 17 - 18 MARCH 1993

Session Number

PASSIVE HYDROGEN MASER FREQUENCY STABILITY AND ACCURACY INVESTIGATIONS

N.A.Demidov, A.A.Belyaev, B.A.Sakharov, A.A.Uljanov
Institute of electronic measurements KVARZ Nizhny Novgorod Russia

F.L.Walls
National Institute of Standards and Technology Boudler USA

Abstract

Frequency stability and frequency accuracy of passive hydrogen maser CH1-76 are investigated. It is noted that together with already investigated frequency maser errors electronic part of the instrument contributes essentially to passive hydrogen maser instability. The influence of electronic units on output frequency of the instrument is analysed.

By the results of investigations of the series of CH1-76 passive hydrogen masers the possible error limits and frequency reproducibility inserted by electronic units of the instrument are experimentally defined CH1-76 passive maser instability is obtained experimentally and is described by the expression:

$$\sigma(2,\tau) = (5\text{-}9)\cdot 10^{-13}\tau^{-0,5} \quad 1<\tau<10^{4}s$$

and $(4\text{-}7)\cdot 10^{-15}$ per day.

Keywords: Hydrogen maser, frequency stability.

1. Introduction

Passive hydrogen masers, developed during last ten years, successfully combine the highest frequency stabillity and small dimentions of table instrument. Passive hydrogen maser frequency stability is better 10^{-14} per day. This parameter is only a little bit worse than in active hydrogen maser.

High stability of passive maser depends first of all on the quantum physical part (hydrogen discriminator) having a very high quality hydrogen emission line.The main sources of passive maser frequency instability are the same as in an active hydrogen maser and namely: cavity frequency detuning, storage bulb coat ageing, magnetic field and beam flux system instability. However, the detailed passive hydrogen maser investigation showed essential influence of electronic units of instrument on the output signal frequency instability and accuracy. Among them it is necessary to note the discriminator test signal spectrum distortions, irregularity of the receiver amplitude-frequency response and instability of receiver input circuit voltage standing-wave ratio (VSWR).

The investigation results of the CH1-76 passive hydrogen masers produced by IEM KVARZ (Russia) are given in this article. Experimental research was conductes by specialists of IEM KVARZ and independently by the scientists of NIST (USA) in 1991-92 years. [1]

2. Design And Construction of CH1-76 Passive Hydrogen Maser. Quantum Hydrogen Discriminator.

The design of a physical part (quantum discriminator) of the passive hydrogen maser is given in Fig.1.

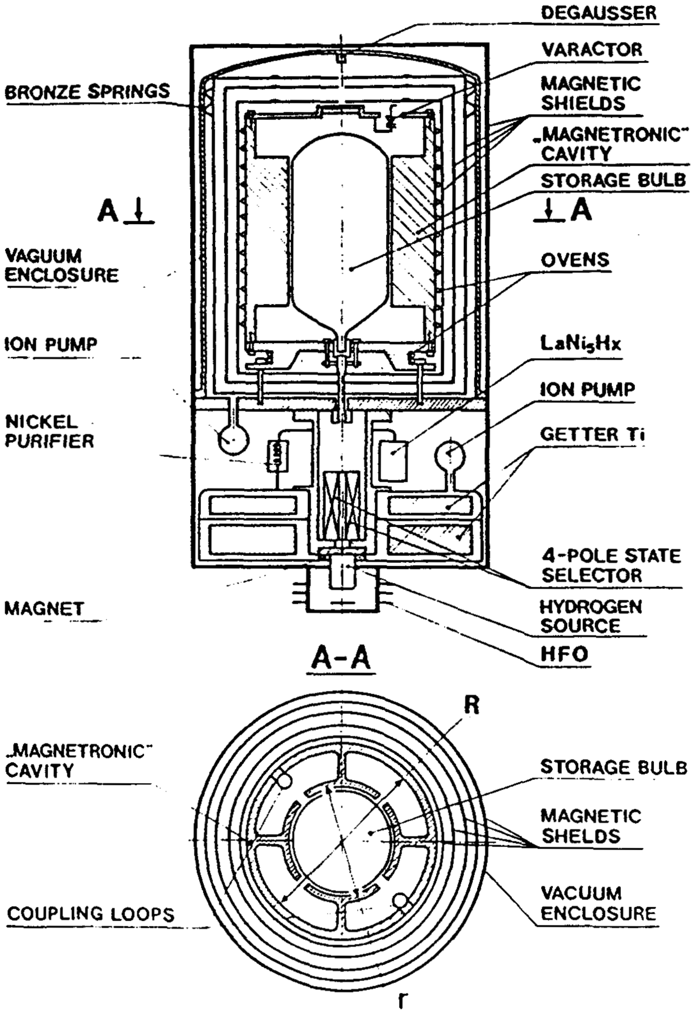


Fig.1. CH1-76 Quantum discriminator

Compaund $LaNi_5H_x$ (about 250g), placed into the metal bulb, is used as molecular hydrogen source. It comprises 20-25 litres of hydrogen at normal pressure that is quite enough for a 5 years continuous maser operation. The bulb with molecular hydrogen is vacuum-tightly connected to purifier. Nickel tube of 0.5 mm diameter and 0.05 mm wall-thickness coiled for compactness is used as purifier. The hydrogen flux is controlled by purifier temperature. Purifier power consumption is about 1W.

Atomic hydrogen source is made of quartz glass in the form of cylinder of 30 mm diameter and 40 mm height. The source is connected to the vacuum pump by indium gasket. Output source channel (collimator) is a set of 200-250 channels of 13 μm diameter and 0.65 mm length each. It provides for hydrogen atom beam flux.

Hydrogen dissociation is performed by molecular impact ionization in electromagnetic field of RF-generator coil. RF-generator power is 12W.The magnetic state selection is performed by means of quadripole magnet. The bore diameter of the magnet is 1.6 mm, its length is 75 mm and outer diameter is 30 mm.The magnetic induction at the pole tips is 1T.

The maser has two separated vacuum chambers. The first one includes storage bulb, state selector magnet and atomic hydrogen source, the second one includes cavity ovens and magnetic shields. Such a construction permits to achieve excellent vacuum- conditions in the storage bulb. Hydrogen pumping is performed by means of absorption pump with titanium as getter material. The getter is activated at 800^0C by an internal tungsten heater. The weight of getter is 1kg which is sufficient for more then 5-7 years of continuous operation. Residual gases are pumped in both vacuum chambers by a 2 l/s ion pumps.

The storage bulb is made of quartz glass in the form of a cylinder of 0.45 l volume. The inner surface of the bulb is coated with 3 layers of fluroplastic, type F-10. Among other known materials F-10 ensures the smallest wall-shift and the largest emission line quality (Q~10^9).

The storage bulb is located in the middle of "magnetronic" cavity [2] Fig.1.Such cavity construction ensures high mechanical rigidity and reliability, high Q-factor (Q~10^4) and a good filling factor value η. Variations of the ηQ_c -parameter versus the internal cavity plates radius is shown in Fig.2.

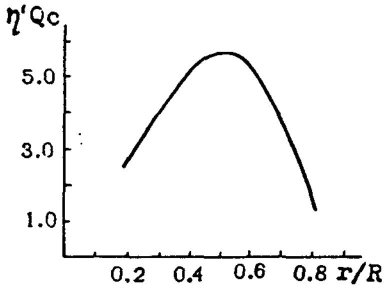


Fig.2. Variation of the filling factor versus the internal plate magnetronic cavity relative radius.

These results have been received theoretically [3] and proved by a real maser parameter measurements. Fig.2 shows that maser operates near the self-excitation point and ensures high signal amplification and discriminator characteristic steepness.

Thermal cavity stabilization is insured by the two-zone oven, placed in vacuum. The temperature is controlled to 1 10^{-2} ^{0}C at the 5-40^{0}C environmental temperature range. CH1-76 maser real warm-up time is about 6 hours at 20^{0}C. Oven power consumption is <1W.

Maser has a four layers permalloy magnetic shield system. Three of them are located in vacuum and made of 81 NMA permalloy of 0.5 mm thickness. The fourth shield made of 79 NMA permalloy covers all discriminator construction with vacuum pumps and hydrogen beam source. To prevent undesirable mixing of Zeeman sub-levels in the drift region, a ring magnet is placed on the discharge bulb of the hydrogen beam source to assure a smooth transition between the quadripole magnet and the apertures of the magnetic shields.

Discriminator weight is 19.5 kg, diameter 224 mm, height 520 mm.

Block-diagram of CH1-76 is given in Fig.3.

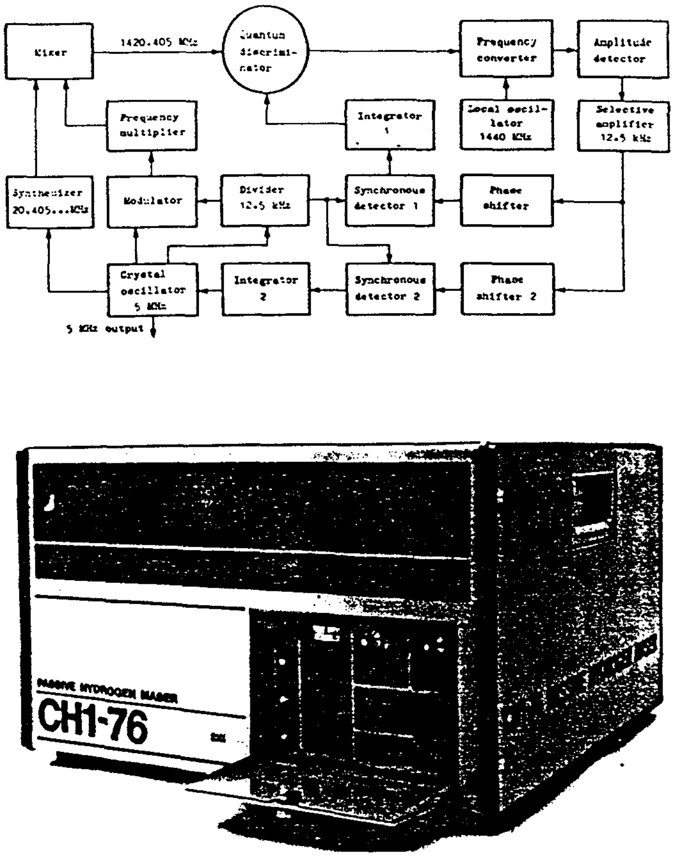


Fig.3. CH1-76 Passive hydrogen Maser: a) block-diagram
b) photo.

It comprises two frequency lock-loops: 5 MHz crystal oscillator frequency lock to the hydrogen emission line and discriminator RF-cavity frequency adjustment loop to the crystal oscillator frequency. The frequency modulation auto-tuning method with high modulation frequency in both loops was used in CH1-76 passive hydrogen maser [4]. 5 MHz crystal oscillator signal phase is modulated by the 12.5 kHz signal, multiplied up to 1400 MHz frequency, mixed with the synthesizes 20.4057 MHz signal and put in the RF-cavity of quantum hydrogen discriminator. The power of this test signal is ~$1\cdot 10^{-12}$W and frequency modulation factor is 1.5.

Error signals (information about the test signal frequency detuning relative to the hydrogen emission line and RF-cavity) are formed as a result of test signal spectrum linear distortions which appear as a result of interaction of the emission line, RF-cavity and test signal in the discriminator. Error signals are contained in the 12.5 kHz amplitude modulation of the output discriminator signal. Low noise (NF~1.5dB) RF-converter (receiver) provides sufficient signal amplification for amplitude detection and the 1440MHz local oscillator eliminates the influence of synchronous disturbances (5 MHz harmonics and 20.405MHz signal) influence in the intermediate frequency amplifier [5].Error signals from crystal oscillator and RF- cavity are divided into two ways by the phaze- shifters setting at the 90^0 angle and entered to the frequency control circuits.

Open-loop proportional-action coefficients are $1\cdot 10^7$ for the crystal oscillator loop and $1\cdot 10^4$ for the RF-cavity loop. Total frequency statical tuning error for 5 MHz output signal is less than $1\cdot 10^{-15}$.

3. Frequency Accuracy and Instability of Passive Hydrogen Maser.

Quantum Discriminator

Physical effects causing hydrogen discriminator frequency variations are the same as in an active hydrogen maser and well known [6,7]. They are: cavity pulling, magnetic fields, storage bulb aging, second-order Doppler shift, spin-exchange shift. Frequency shift values and their instabilities are shown in Table 1.

Table 1

Physical effect	Shift value	Shift instability	Note
1. Cavity pulling	$-(2\text{-}5)\cdot 10^{-12}$	$2\cdot 10^{-15}$	Due to used method of tuning and spin-exchange shift
2. Magnetic fields	$2.5\cdot 10^{-13}$	$-2\cdot 10^{-14}/\mathrm{Oe}$	
3. Wall-shift of storage bulb coating	$6.7\cdot 10^{-12}$	$6\cdot 10^{-13}/^0\mathrm{C}$	Possible changing up to $+1.5\cdot 10^{-13}/$ year
4. Second-order Doppler-shift	$-4.46\cdot 10^{-11}$	$-1.4\cdot 10^{-13}/^0\mathrm{C}$	

The passive hydrogen maser feature is the relatively large cavity pulling frequency shift arising due to used method of tuning and spin-exchange emission line shift. Cavity-pulling frequency shift may be significantly decreased by special test signal spectrum pre-distortions.

Electronics

Passive hydrogen maser short-term frequency stability depends on the quantum discriminator characteristic steepness and the noise figure of preamplifier in the receiver, which define the low frequency (< 10 Hz) white noise level of the output 5 MHz signal phase noise spectrum.

In practice it is very convenient to estimate discriminator quality in combination with electronic part of the instrument. Normal FM test signal is entered to the discriminator and the amplitude detector output voltage change is measured at the calibrated test signal carrier frequency shift by a half of hydrogen amission line- width. As a result of measurement, the discriminator quality factor is calculated:

$$R = U_s / U_n \Delta f \qquad (1)$$

where U_s - is the 12.5 kHz voltage change at the amplitude detector output

U_n - noise voltage at the amplitude detector output without frequency detuning between test signal carrier and emission line in the 1 Hz bandwidth $[\mathrm{V}/\sqrt{\mathrm{Hz}}]$

Δf - hydrogen emission line-width

For the CH1-76 passive hydrogen maser the quality factor value is within the limits 300:400 and ensures 5 MHz output signal short-term frequency stability $(5\text{-}9)\ 10^{-13}\tau^{-0.5}$ for the time intervals $1<\tau<1\ 10^4$ s

Due to the used modulation method of tuning in the passive maser and detuning information contained in the weak amplitude modulation signal, the electronic part influence on the long-term maser stability and accuracy will be manifest itself as an additional amplitude modulation at the same modulation frequency 12.5 kHz.

This additional modulation signal can appear as a result of FM test signal spectrum distortions in several units of instrument: modulator, frequency multiplier and receiver.

Modulator

The main requirements to the phase-modulator of the instrument are the highest linearity of modulation characteristic and the reduction of the even harmonics in the modulation signal. The presence of even harmonics of the modulation signal [8] leads to the test signal spectral components distortions and gives an additional amplitude modulation signal and frequency shift of output 5 MHz signal. The estimation of this shift for CH1-76 passive maser can be done by the next formula [8]

$$\Delta f/f = 3 m_l / 4 Q_l, \qquad (2)$$

where: m_l is the 2-nd harmonic modulation index

Q_l is the emission line quality factor $1\cdot 10^9$

According to expression (2) the m_l value should be less then $1\cdot 10^{-4}$ to achieve 5 MHz output frequency shift less $1\cdot 10^{-13}$. And, consequently, the second harmonic of modulation signal reduction of the test signal should be more than 80 dB. In CH1-76 passive hydrogen maser these values are achieved by a special type of a varactor with very high linearity of capacity-voltage characteristic and usage of even harmonic reduction modulation signal former.

Frequency Multiplier

Additional amplitude modulation FM signal arises in the frequency multiplier due to FM-spectrum distortions by the multiplier steps resonant systems. This effect leads to the RF discriminator cavity adjustment frequency shift and therefore to the emission line frequency shift (cavity pulling). Maser output 5 MHz signal frequency shift value in this case is proportional to the multiplier resonant system detuning and quality factor and can be estimated by the expression

$$\Delta f/f = [Q_s/Q_l Q_c]\cdot[J_1(m_s)/J_1(m_c)]\cdot[\Delta f_s/f_s]\cdot[f_c/f_s] \quad (3)$$

In expression (3) f_s, Q_s, Δf_s are the frequency, quality factor and detuning of multiplier step resonant system; Q_l, Q_c - are the quality-factors of emission line and RF-cavity in the discriminator; $J_1(m_s)$ and $J_1(m_c)$ are the first modulation harmonic component FM-spectrum amplitudes in the multiplier step and in the RF-cavity.

Frequency multiplier contribution to long term passive maser frequency stability depends on the temperature stability and ageing of multiplier steps resonant circuits and can reach a few part $1\cdot 10^{-13}$. For supression of this effect multiplier has several amplitude-limiters and automatic output voltage control system providing 12.5 kHz amplitude modulation suppression up to -110 dB and eliminating the multiplier influence on the output frequency stability.

Reciever (frequency converter)

Reciever's circuit influence on the output standard frequency arise the same way as in frequency multiplier due to the AFC unlinearity. However it is impossible to use the amplitude modulation suppression here because the reciever's signal envelope contains useful information. To reduce an additional amplitude modulation the reciever's intermediate amplifier bandwidth is made as wide as possible provided that signal/noise ratio is > 1. IF amplifier in CH1-76 has ~20 MHz bandwidth at 19.6 MHz carrier and the output standard frequency shift accoding to expression (3) less then $3.5\cdot 10^{-13}$ for $\Delta f_s / f_s = 5\%$ and the temperature stability of this shift less $5\cdot 10^{-15}/^o\mathrm{C}$

Experimentaly defined that the RF-discriminator cavity tuning point in the passive hydrogen maser cavity tuning system being described depends on the RF-cavity and reciever coupling and output standard frequency changes with the VSWR of the reciever input and coaxial cable length (Fig.4.)

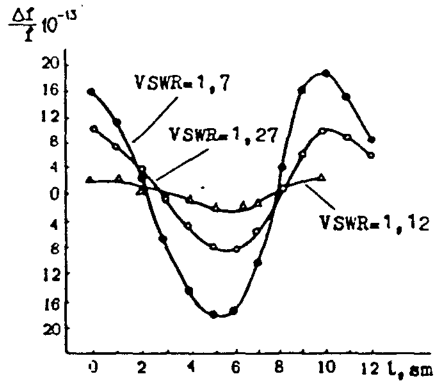


Fig.4. 5 MHz output frequency variations versus coaxial cable length coupling guantum discriminator and the reciever.

This effect was not investigated theoretically and one of the probable reasons is the RF-cavity resonant curver distortions by the load reactivity.

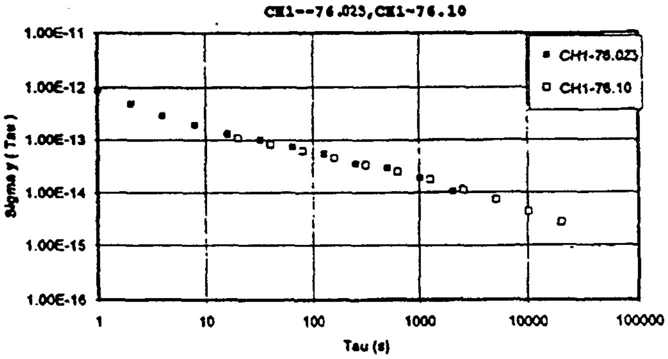
4. Experimental Results

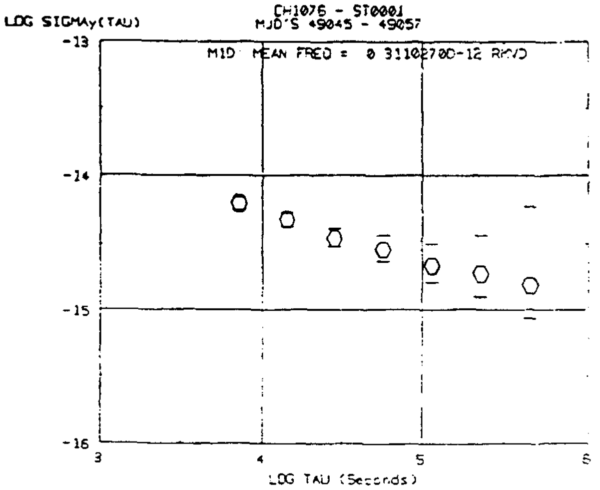
Frequency stability measurement tests of the CH1-76 type passive hydrogen masers were conducted at IEM KVARZ and independently at NIST (USA). Frequency accuracy, frequency drift, time-domain and long term frequency stability, frequency temperature coefficient and phase noise spectrum are estimated.

Short term frequency stability (Allan deviation $\sigma(2,\tau)$ (Fig.5) for most of masers is within the limits $(5:9)\cdot10^{-13}$ for a 1 S and for the time intervals $1<\tau<1E{+}4$ s may be expressed as

$$\sigma(2,\tau)=(5\div9)\cdot10^{-13}\tau^{-0,5}$$

For a long time intervals $\sigma(2,\tau)$ decreases slowly and is estimated as $(4:7)\cdot10^{-15}$ per day and depends on the environmental conditions.





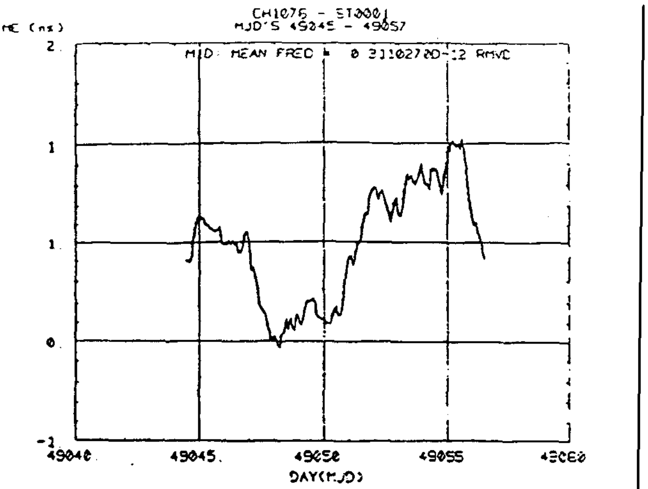


Fig.5 CH1-76 5 MHz output signal freguency stability (Allan deviation)

Typical frequency drift estimations are less then $1\cdot10^{-15}$ per day, but CH1-76 serial number 023 accoding to NISTestimation showed the frequency drift value $-1.82\pm0.06\cdot10^{-15}$ per day for the 100 days time interval. Long term CH1-7 6 frequency behaviour is represented in Fig.6 with respect to environmental temperature. Frequency temperature coefficient experimental estimations for several samples of CH1-76 is $(0.5\div1.5)\cdot10^{-14}$/C.

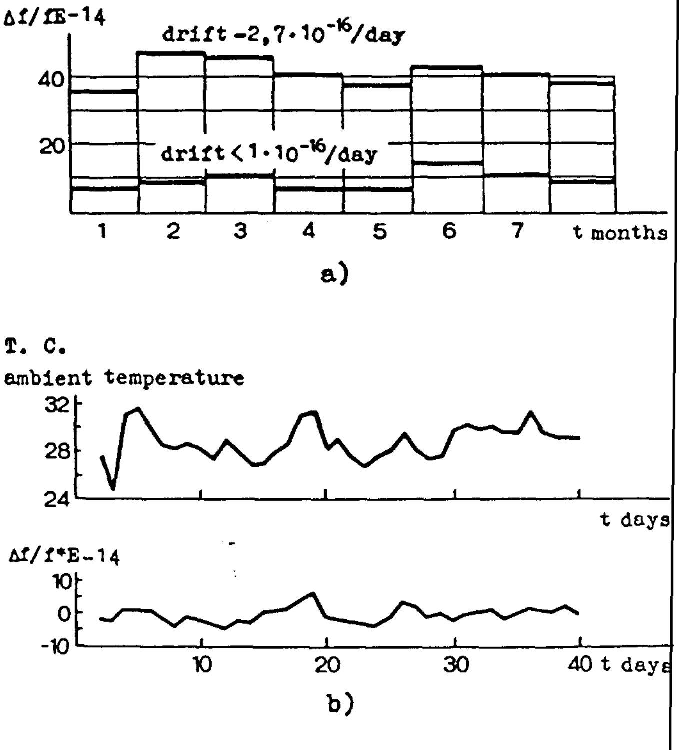


Fig.6 Long term frequency stability of the CH1-76 passive hydrogen masers

a) averaging per month

b) averaging per day with respect the ambient temperature

Phase noise spectrum of the CH1-76 5 MHz output signal is shown at the Fig.7.

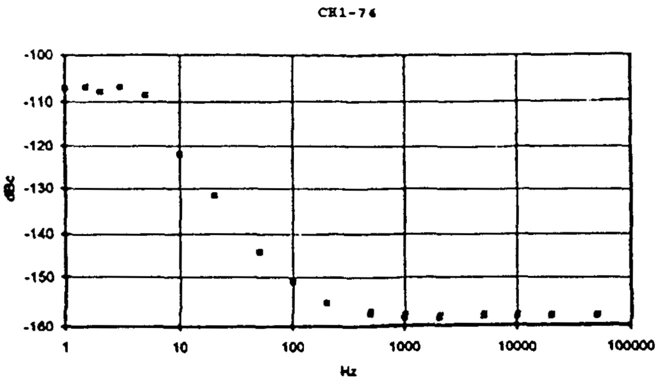


Fig.7 Phase noise spectrum CH1-76 5 MHz output signal

References

1.F.Walls, D.Allan, J.Gray, C.Hackman. Calibration of KVARZ Passive hydrogen maser CH1-76/2391 for Efratom Division Ball Corporation. NIST, 1992

2.A.A.Belyaev, N.A.Demidov, S.A.Makarychev. Hydrogen maser. A.s. No1459568 USSR Otkrytiya Izobreteniya No 6, 1989

3.A.A.Belyaev, N.A.Demidov, V.A.Savin Hydrogen maser SAS- cavity energetic characteristics investigation Technica sredstv svjasy RIT 1987 No 2 p.23

4.G.Busca,H.Brandenberger Passive H-maser Proc. 33-rd Ann.Freq.Cont.Symp, 1979 p.563-568

5.N.A.Demidov, B.A.Sakharov Passive H-maser A.s. No1.258.212 USSR Otkrytiya Izobreteniya No 34 1986

6.E.M.Mattison Physics of Systematic Frequency Variations in Hydrogen Masers IEEE Transacytions on ulrasonics, ferroelectrics and frequency control vol 39 No 2 March 1992

7.F.Walls Characteristics and Perfomance of miniature NBS Passive Hydrogen maser. IEEE Transactions on instrumentation and Measurement vol IM-36 No 2 June 1987

8.V.A.Logachev Investigation of passive hydrogen maser frequency stability Technica sredstv svjazy, RIT, No 1 1986 .