Some Experimental Results with an Atomic Hydrogen Storage Beam Frequency Standard*

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Abstract

A frequency standard is described in which a quartz crystal oscillator is locked to the hydrogen hyperfine transition using the dispersion of this resonance. The hydrogen storage beam apparatus closely resembles a hydrogen maser with a low-Q cavity below oscillation threshold. Cavity pulling can be reduced to a point where environmental temperature fluctuations limit the stability mainly via the second-order Doppler effect. Locking to the dispersion feature of the resonance eliminates the need for frequency modulation in order to find line-center. The stability of the frequency standard was measured against crystal oscillators and cesium beam frequency standards; stabilities of 4×10^{-13} were recorded for sampling times of 30 seconds and of 3 hours.

Introduction

As compared to the hydrogen maser oscillator, a passive hydrogen standard offers a significant reduction in cavity pulling [1, 2]. This, together with the elimination of the requirement to obtain self-oscillation, offers considerable design advantages, might lead to improved long-term stability, and possibly offers greater flexibility to evaluate the frequency bias due to wall-collisions of the stored hydrogen atoms (wallshift) [3].

Based on certain theoretical considerations, a hydrogen storage beam tube employing the detection of hydrogen atoms is an appealing design[1] [2, 4]. However, an efficient, low-background hydrogen detector is essential to exploit the advantage given by hydrogen atom detection as compared to the detection of the microwave power. Unfortunately such a detector is not yet available.

For a passive device, based on detecting the microwave signal which is transmitted through the cavity containing the hydrogen atoms J. Viennet, C. Audoin and M. Desaintfuscien have shown [1] that the cavity pulling factor is

$$F = \frac{Q_c}{Q_l} \frac{1}{2 - \alpha} \tag{1}$$

Here Q_c and Q_l are the cavity and line quality factors, respectively; and α is a gain parameter [for negligible saturation the gain is equal to $\frac{1}{1 - \alpha}$ at resonance]. Information on the hydrogen line can be obtained by either detecting the microwave intensity or by detecting the dispersion signal. Since the dispersion signal contains the frequency information, its use avoids the

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[1] We have built and operated such a device and have demonstrated the basic feasibility of the concept. We recorded the hydrogen resonance line via detection of hydrogen atoms which left the storage bulb through a separate exit opening and passed through a second state selector.

need for frequency modulation; however, the hydrogen flux has to be modulated in order to substract — in first approximation — the dispersive characteristic of the microwave cavity.

Apparatus

The block diagram of our apparatus is depicted in Fig. 1. The 5-MHz signal from a quartz crystal oscillator is multiplied by a factor of 288 and mixed with a signal from a synthesizer (about 19.594 MHz) to generate a signal at approximately the hydrogen transition frequency. This signal, which can be swept
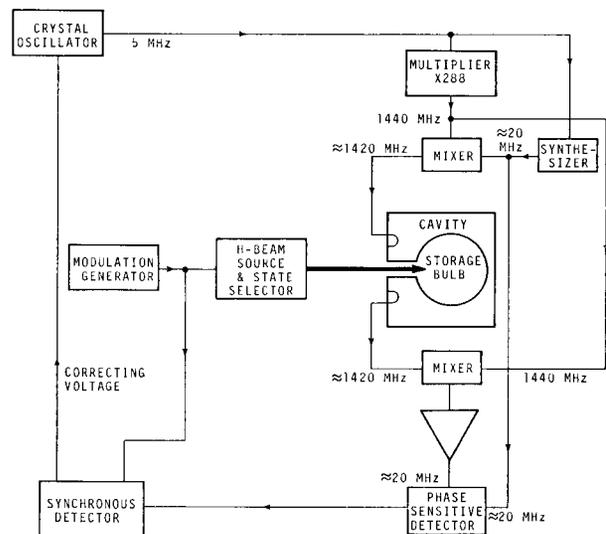

Fig. 1. Block diagram of the Atomic Hydrogen Beam Frequency Standard. Phase-shifters and isolation devices not shown

across the hydrogen resonance by sweeping the synthesizer frequency, is transmitted through the microwave cavity and mixed again with the signals from the multiplier and synthesizer. Amplification before the last mixing yields a good output at the last mixer (phase-sensitive detector) thus avoiding possible limitations due to low frequency noise (flicker noise) in the phase-sensitive detector and the circuits following it. Not shown in Fig. 1 are the isolators, necessary to decouple the circuits connected to the output of the microwave cavity from those at its input, and the phase-shifters.

The output of the phase-sensitive detector is proportional to the imaginary part of the complex cavity response. If the cavity contains state-selected hydrogen atoms and is tuned to their transition frequency, the hydrogen resonance is observable at the output of the phase-sensitive detector as a phase-change due to the corresponding dispersion. In order to obtain the favorable frequency pulling factor of Eq. (1), i.e., in order to subtract the cavity response, we modulate the hydrogen beam intensity at a relatively low rate, e.g. 1 Hz. The output of the phase-sensitive detector which contains the phase information about the hydrogen resonance (now modulated also at 1 Hz) is fed into a synchronous detector ("lock-in amplifier"). Its amplified and filtered output serves as the correcting voltage for the crystal oscillator. The locking criterion is thus a vanishing phase-change under modulation of the intensity of the hydrogen beam entering the cavity. The hydrogen beam apparatus resembles closely a conventional hydrogen maser oscillator except for the lower cavity-Q which places it significantly below threshold (see section: Experiments).

At this point it should be noted that in storage devices such as ours, the strength of the signal due to the hydrogen atoms as well as the associated linewidth will increase as the interrogating power increases; there is no optimum power [5, 6] as in beam tubes (see Appendix). In the Appendix we show that a typical power P_t can be defined for which the transition probability is $\frac{1}{4}$ and the linewidth is

$$W_t = \frac{\sqrt{2}}{\pi} \gamma \qquad (2)$$

where γ is the escape relaxation constant for the stored hydrogen atoms.

Experiments

We used in our first experiments a storage bulb of 10 cm diameter with a calculated storage time (escape relaxation time) of 0.1 s. The corresponding linewidth at the typical power P_t follows from Eq. (2) as $W_t = 4.5$ Hz. We operated at beam intensities which are comparable to those used in hydrogen maser oscillators. From previous experience we know that the cavity-Q for some oscillation threshold beam intensity I_{th} at storage times of about 1 s is approximately 30000. Since the oscillation threshold condition depends on the square of the storage time, the (fictitious) threshold cavity-Q for our device operating at beam intensities of about 30 I_{th} is approximately $Q_{c,th} \approx 90000$. We reduced our cavity-Q to $Q_c \approx 2500$ by over-critically coupling to the output load of the cavity. Thus, our system was operating at the fraction $\alpha = Q_c/Q_{c,th} \approx 0.028$ of oscillation threshold.

From Eq. (1) we calculate the pulling factor to be $F \approx 4 \times 10^{-6}$. This is one order of magnitude less than in the case of a typical hydrogen maser oscillator. Since environmental temperature fluctuations are the dominant cause for cavity detuning, the above pulling factor puts us close to a fractional frequency change of 1×10^{-12} per kelvin for our fused quartz cavity[2].

The hydrogen dispersion signal, as measured at the output of the phase-sensitive detector, is depicted in Fig. 2. The horizontal scale is indicated on the figure; the recording was made with a time constant of

10^{-3} s; the hydrogen beam was not modulated. A high-resolution recording of the output signal of the synchronous detector is shown in Fig. 3. The horizontal scale is shown on the figure; a time constant of 10 s was used. The hydrogen beam was modulated by turning the hydrogen discharge on and off at a 1-Hz frequency. The linewidth of about 5 Hz agrees with the predicted value.
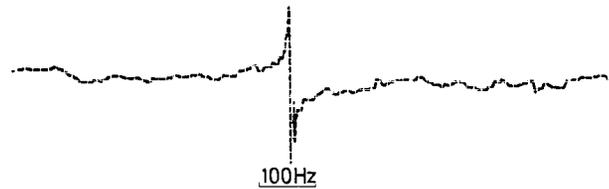

Fig. 2. Hydrogen dispersion signal as measured at the output of the phase-sensitive detector (open-loop operation). No beam modulation. Recording time constant: 10^{-3} s. Sweep speed: 5.6 Hz/s
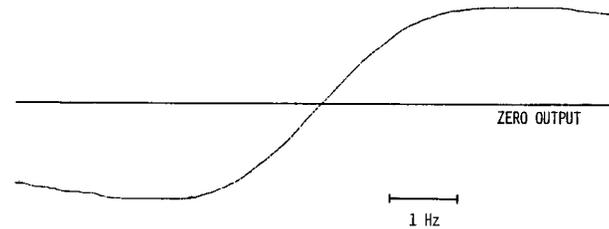

Fig. 3. Hydrogen dispersion signal as measured at the output of the synchronous detector (open-loop operation). Beam modulated at 1 Hz. Recording time constant: 10 s. Sweep speed: 0.022 Hz/s
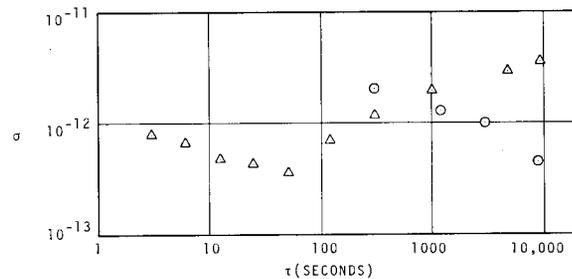

Fig. 4. Frequency stability of the device of Fig. 1 measured against a crystal oscillator (triangles) and a cesium beam frequency standard (circles). The square root of the Allan variance $\sigma_y^2(N, T, \tau, B)$ is plotted where: number of samples $N = 2$, deadtime $T - \tau = 0$, and bandwidth $B = 30$ Hz. The sampling time τ is the variable, and y denotes fractional frequency fluctuations

We operated the system as a frequency standard, i.e., we locked the crystal oscillator to the resonance, as shown in Fig. 1. The frequency stability was measured against (commercial) cesium clocks used in the NBS time scale and against crystal oscillators. A typical result is depicted in Fig. 4 where the square root of the two-sample Allan variance [7] is plotted versus the sampling time. The circles are values obtained against a cesium clock; the triangles represent

a measurement against a crystal oscillator. The best stabilities, with values of 4×10^{-13}, were measured at sampling times of $\tau = 30$ s and of $\tau = 3$ h. Basically, Fig. 4 depicts the performances of a particular crystal oscillator and a particular cesium beam frequency standard. The instability due to the atomic hydrogen storage beam frequency standard does not show up, i.e., its performance apparently is equal to — or possibly better than — the crystal oscillator and the cesium beam frequency standard in their respective ranges. From the signal-to-noise ratio of Fig. 2 we calculate a frequency stability of about 5×10^{-11} for a sampling time of 10^{-3} s. This agrees qualitatively with the results of Fig. 4.

Conclusions

We have described dispersion-locking of a crystal oscillator to the atomic hydrogen hyperfine resonance. The resulting frequency standard device shows a promising frequency stability performance. The reduced cavity pulling factor may lead to improved long-term frequency stability and/or to a simplified design of the apparatus as compared to the hydrogen maser oscillator. The cavity pulling factor could be reduced to the point where the second-order Doppler effect $(1.4 \times 10^{-13}/\text{kelvin})$ would determine the requirements for thermal stabilization. The wallshift may become more conveniently evaluable; for this, cavity pulling could be reduced further to allow changes of the shape of the storage bulb without the need for retuning the cavity [8, 9] or perhaps with a simple resetting of the cavity by external sensing of the detuning.

The spin exchange frequency shift enters explicitly as a frequency bias which must be evaluated and can be evaluated with the device described in this paper. However, this bias is expected to not exceed a few parts in 10^{13} for typical operating conditions [10], and its direct, precise measurement appears to be desirable in view of some doubts about the total validity of the compensation of spin exchange shift by cavity pulling in the cavity tuning procedure of the maser oscillator [11].

Appendix

The probability density $f(t)$ for an atom to stay for some time t in the storage bulb is given by

$$f(t) = \gamma e^{-\gamma t} \qquad (3)$$

where γ is the escape relaxation constant.

This exponential distribution function leads easily to the transition probability T for an ensemble of stored atoms [12].

$$T = \frac{1/2\, \chi^2}{(\omega - \omega_0)^2 + \gamma^2 + \chi^2} \, . \qquad (4)$$

where

$$\chi = -\frac{\mu H}{\hbar} \, . \qquad (5)$$

In Eq. (5), μ is the magnetic dipole moment of the transition and H is the average microwave signal amplitude in the interrogation region. The power delivered by the atoms to the cavity is then $n T \hbar \omega_0$ where n is the flux of atoms in the upper state minus the flux of atoms in the lower state. We see that at resonance T has no maximum but approaches asymptotically $T = \frac{1}{2}$ for arbitrarily large excitation $(\chi \to \infty)$.

The line will broaden with increasing excitation. From Eq. (4) we get for the linewidth

$$W = \frac{1}{\pi} \, (\gamma^2 + \chi^2)^{1/2} \, . \qquad (6)$$

We define a typical microwave power P_t with a corresponding perturbation parameter χ_t and a linewidth W_t by setting

$$\chi_t^2 = \gamma^2 \, . \qquad (7)$$

This leads to $T_t = \frac{1}{4}$ and $W_t = \frac{\sqrt{2}}{\pi} \, \gamma$.

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[3] Strictly, Eq. (3) is not completely true because we have a cutoff at very short times due to the physical necessity for the atoms to traverse the storage bulb at least once before escaping.