A NEW KIND OF PASSIVELY OPERATING HYDROGEN FREQUENCY STANDARD*

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ABSTRACT

The philosophy behind a new design of a passively operating hydrogen frequency standard will be described. Basically the hydrogen atoms are stored in a conventional, coated quartz bulb, which is contained in a TE_{011} cavity. The H-atoms are interrogated by driving the traditional 1,0 to 0,0 transition with an external frequency source and comparing the amplitude and/or phase of the output signal from the cavity with the input signal. The goal of this design is to achieve long term frequency stability of better than 1 part in 10^{14} for measurement times from 1 day to 1 year. This is done by increasing the cavity linewidth and decreasing the hydrogen resonance linewidth as compared to typical values for an oscillating maser.

The possibility of significant size reductions based on the use of small dielectric cavities and lower beam intensities, at little or no sacrifice in long term stability, is pointed out.

A new cavity control servo is described which allows the rapid stabilization of the cavity resonance frequency to better than 10^{-14} in its effect of pulling the hydrogen resonance. The reduction of other systematic effects to below 10^{-14} fractional frequency uncertainty and instability is discussed, including spin exchange and magnetic interactions.

INTRODUCTION

The purpose of this paper is to describe the design and report some preliminary measurements on a new kind of passive hydrogen frequency standard which shows great promise of achieving stabilities of better than 1×10^{-14} for averaging times from one day to perhaps a year. In addition, we hope to prove that the design concepts brought forth in this passive H-maser approach allow one much greater flexibility in trading various parameters off against one another in order to satisfy other criteria, such as the reduction of size or of selected systematic effects.

For timekeeping applications the goal is to minimize the time dispersion over many days or even years [1]. Presently, the best that can be done with any frequency standard, including hydrogen and cesium standards, is several parts in 10^{-14} per year [2] -- the only probable exceptions being the primary cesium standards. Requirements in navigation (Global Positioning System) are roughly equivalent to a frequency stability of 1×10^{-14} for 1 to 10 days [3]. It has been the requirement for very good long term stability, rather than the quest for absolute accuracy, which motivated us to look at the possibilities offered by passive hydrogen devices.

Before embarking on the analysis of systematic effects--the elimination of which is the real essence of good long term stability--we want to briefly decribe a typical active or self-oscillating hydrogen maser and several passive hydrogen standard options.

Hydrogen frequency standards, whether active or passive, are based on the $F = 1$, $m_F = 0$ to $F = 0$, and $m_F = 0$ hyperfine transition at 1420 MHz in the ground state of atomic hydrogen, which is illustrated in Fig. 1 [4,5]. Production and state selection of the atomic hydrogen is typically accomplished via the scheme shown in the lower portion of this figure. The state selection magnet shown is a hexapole but could be a different configuration.

Figure 2 shows a block diagram of a typical active hydrogen maser. By adjusting various parameters such as hydrogen beam intensity, storage time, cavity Q, etc., the energy radiated by the hydrogen atoms can be made to exceed cavity losses, and the system breaks into oscillation.

The weak signal of 10^{-12} to 10^{-13} W is then phase compared with a local oscillator, using multiplication and heterodyne techniques in order to preserve signal-to-noise. The output of the phase comparator is then used to phase-lock the local oscillator to the hydrogen signal. Note that in an active hydrogen maser no microwave signal is injected into the cavity.

Several passive hydrogen frequency standards have been proposed in the past. The first passive frequency standard was proposed and a prototype built by H. Hellwig in 1970 [6,7]. A simplified block diagram is shown in Fig. 3, which is similar to Fig. 2 except for the addition of a signal that is injected into the cavity region. Phase comparison of the output signal with the input signal allows one to frequency lock the local oscillator to the hydrogen phase dispersion signal. Fig. 4 shows such a hydrogen dispersion signal. The hydrogen signal was separated from other dispersive effects by squarewave modulating the H signal at ≃ 1 Hz via hydrogen beam modulation or Zeeman quenching and detecting the resulting phase modulation with a ≃ 1 Hz synchronous detector. Stabilities of $\simeq 2 \times 10^{-12}\,\tau^{-1/2}$ in a 30 Hz bandwidth were observed with this system [7]. Our present design is an outgrowth of this work. Figure 5 shows a hydrogen beam tube built and tested in 1971 [8]. This beam tube featured a linewidth similar to the active maser and detection of the hydrogen atoms, which had undergone the appropriate transition. As we will see later, this approach virtually eliminates cavity pulling. However, the then available detectors for thermal hydrogen atoms in arrangements which had sufficiently narrow linewidths had poor signal-to-noise, which prevented the attainment of good stabilities in a reasonable time.

H. Peters proposed and built in 1971 a beam tube with cooled hydrogen atoms not using any storage bulbs [9]. This reduced cavity pulling and eliminated wall shifts while featuring good signal-to-noise. However, the linewidth was much wider.

Figure 6 shows the block diagram of our presently operating passive hydrogen maser design. It uses a conventional beam system to produce the state selected atomic hydrogen. The cavity is of standard size and presently has a loaded Q of almost 40000. The design and the reasons behind it will be discussed in detail in the context of reviewing various systematic effects.

Basically, a 5 MHz oscillator is multiplied and mixed with a synthesizer output to produce the hydrogen resonance frequency. This microwave signal is then injected into the cavity and allowed to interact with the cavity and the hydrogen atoms. The output signal is then processed in order to frequency lock the local oscillator to the hydrogen resonance and the TE_{011} cavity resonance to the local oscillator.

TABLE 1

DEVICE	Q_{CAV}	Q_H	K	$\nu_{CAV} - \nu_H$ (Hz) FOR $\frac{\nu - \nu_H}{\nu_H} = 10^{-14}$
CONVENTIONAL ACTIVE MASER	35,000	1×10^9	3.5×10^{-5}	0.4
PASSIVE MASERS:				
PRESENT NBS MASER	40,000	5×10^8	8×10^{-5}	0.2
DIELECTRIC CAVITY	5,000	2×10^9	2.5×10^{-6}	5.7
HIGH-Q CAVITY HIGH-H-Q	40,000	1×10^{10}	4×10^{-6}	3.5

TABLE 2

$\bar{H}$	$\Delta\nu_z$	$\left[\frac{\Delta H}{H}\right]$	SHIELDING FACTOR 10^{-4} T Ext Field
1×10^{-8} T	2.7×10^{-5} Hz	25%	4×10^4
1×10^{-7} T	2.7×10^{-3} Hz	0.25%	4×10^5
2×10^{-6} T	1.1 Hz	.0006%	1.6×10^7

The significant systematic effects which trouble hydrogen frequency standards are:
1) Cavity pulling, 2) Magnetic field, 3) Crampton effect [10], 4) Second-order Doppler, 5) Wallshift, and 6) Spin exchange.

Cavity Pulling

In our opinion the most serious limitation to long term stability is cavity pulling. Approximate equations [11] governing this effect are:

$$\nu - \nu_H \quad K(\nu_{CAV} - \nu_H)$$

$$K \simeq \left(\frac{Q_{CAV}}{Q_H}\right)^2$$

DETECTION OF ATOMS
(FAR BELOW OSCILLATION THRESHOLD)

$$K \simeq \left(\frac{Q_{CAV}}{Q_H}\right)$$

DETECTION OF rf
(ALL MASERS, ACTIVE & PASSIVE)

After looking at the equations it is easy to understand the early enthusiasm for the passive hydrogen beam frequency standards, which detected atoms, as they virtually eliminated cavity pulling. All of the present devices sample the field intensity, i.e., all masers - active and passive - suffer from cavity pulling which varies linearly with the ratio of the cavity Q to the line Q, multiplied by the cavity offset.

For a typical active maser the cavity pulling is indicated in Table 1: assuming a cavity Q of 35000 and a line Q of 1×10^9 it is not surprising that many effects are capable of shifting the frequency many parts in 10^{14}. Note that in order to achieve one part in 10^{14} long term stability the cavity must be stabilized to 3 parts in 10^{10}. Obvious sources capable of moving the cavity this amount are cavity temperature, bulb temperature, mechanical strain, electrical changes in the cavity walls, changes in the coupling to the cavity, leakage of radiation from the cavity to the outside, etc., all of which are likely to be functions of time.

One of the primary reasons we have chosen this passive approach is that it allows considerable flexibility to choose design parameters such as cavity Q and line Q in order to reduce cavity pulling because no oscillation threshold conditions have to be met.

In our full-sized cavity design we have chosen to increase line Q to approximately 10^{10}. This will be accomplished by decreasing the hydrogen density in the bulb and increasing the storage time a factor of 10. So far, we have achieved a Q_H of 5×10^9. The physical limit to this approach is ultimately wall relaxation. [12] This reduces the basic sensitivity to cavity pulling as well as the frequency shift and broadening due to spin-exchange collisions by a factor of 10 and reduces by the same factor the amount that the servo has to split resonance line in order to achieve a desired stability. In addition it reduces the required beam intensity by a factor of 100 which has major implications in terms of future size and weight of passive hydrogen frequency standards.

Figures 7 and 8 show a model of the full sized cavity which we are presently using. The cavity length is adjusted by rotating the quartz barrel using a design of R. Vessot [13]. Note that 120 degree rotation changes the length by about 1 cm. The top has a choke flange which is designed to help suppress TM modes in the cavity and eliminate radiation losses from the top of the cavity. The TM modes are troublesome in that they are degenerate with some coaxial transmission modes and hence couple through the gaps around the cavity endplates to the outside. Any change in the outside environment thus affects the TM modes which can then pull the desired TE_{011} cavity mode.

Figure 7 shows a dielectrically loaded TE_{011} cavity with a Q of approximately 6000 along side the standard cavity. The interior of the dielectric shell is the storage bulb. This provides a cavity which is exceptionally rugged and very much smaller than a standard cavity. The cavity pulling sensitivity is also small because of its low Q (see Table 1).

Cavity Servo

In addition to decreasing the inherent sensitivity to cavity pulling, the resonance frequency of the cavity can be easily locked to the H resonance frequency in our passive design. As depicted in Fig. 6, the signal from the 5 MHz local oscillator is phase modulated, multiplied, and mixed to produce a phase modulated 1420 MHz carrier. After transmission through the cavity, the 1420 MHz signal contains amplitude modulation at the fundamental of the phase modulation with intensity and sign determined by the cavity offset. After heterodyning to 20 MHz, the signal (now pure amplitude) is processed by a synchronous detector to correct the cavity frequency via tuning elements connected to the cavity output. Using 12.5 KHz phase modulation we have demonstrated that one can easily reduce the cavity offset to less than 5 Hz in only 20 seconds. Using the large bulb with a hydrogen line Q of 5×10^9 to 10^{10} in the full sized cavity, we can reduce the effect of cavity pulling to below 10^{-14} in about 10 minutes. Therefore changes in the output frequency, due to cavity pulling, should easily be stable to parts in 10^{15} in long term even in the presence of environmental perturbations, due to the low sensitivity to cavity pulling and the high signal to noise which permits a correction of the cavity frequency in a time rapid compared to most environmental changes.

The 12.5 KHz modulation sidebands are 10 dB below the 1420 MHz carrier; the modulation is fast compared to the hydrogen linewidth and the Zeeman separation of approximately 140 Hz. The 12.5 KHz sidebands were measured to remain equal in amplitude to about 10^{-4} after several months of operation. No significant perturbation to the resonance itself occurs using this cavity stabilization technique.

Magnetic Fields

The shift of the resonance frequency due to a magnetic field is ($\Delta\nu_H$ in Hz, H in Tesla, 1T = 10^4 G)

$$\Delta\nu_H = 2.750 \times 10^{11} \; \overline{H^2}$$

where the average is over the entire storage bulb. The average magnetic field is measured via the Zeeman effect $\nu_z = 1.4 \times 10^{10}\; \overline{H}$. Therefore the shift term should be written as

$$\Delta\nu_H = 2.75 \times 10^{11}[\overline{H}^2 + \overline{\Delta H^2}]$$

where $\overline{\Delta H^2}$ is the mean squared field deviation from the average over the bulb as measured via ν_z. In order to keep the offset due to $\overline{\Delta H^2}$ less than 10^{-14}, this term must be kept below $(7 \times 10^{-9}\ T)^2$ or $(70\ \mu G)^2$, which is relatively easy at magnetic fields below 10^{-7}T (1 mG) (see Table 2).

Another systematic effect is a perturbation discussed by Crampton (Crampton effect) [10] which is caused by the presence of radial rf and dc magnetic field components in the storage region coupled to a difference in the populations $\rho_{1,1}$ and $\rho_{1,-1}$ of the 1,1 and 1,-1 states due to the state selection process. This frequency shift $\Delta\nu_{CE}$ is given by

$$\Delta\nu_{CE} = K\gamma_H \left(\rho_{1,+1} - \rho_{1,-1}\right)\left(\frac{\tau_c}{1+(\omega_z\ \tau_c/2)}{}^{4}\right)\left[\frac{H^{rf}_{\vec{r}}}{H^{rf}_{\vec{z}}}\ H^{dc}_{\vec{r}}\right]_{\text{BULB}}$$

where γ_H is the relaxation rate due to spin exchange and τ_c is the average time for a hydrogen atom to cross the bulb. K is $\simeq 2 \times 10^{11}$ Hz $/_T$, subscripts r and z designate radial and axial components of the magnetic fields.

One way to substantially reduce this effect is to operate at fields of 2×10^{-6} Tesla(20 milligauss) where the $\omega_z\ \tau_c$ term reduces the effect by more than 100. Table 2 shows the relationship between magnetic field and required magnetic field stability and shielding factor in order to achieve a fractional frequency stability of 1×10^{-14}, we see that this solution is unacceptable for achieving long term stability, as it requires a stability of residual magnetic fields of 1×10^{-11} T (0.1 μG) which is very difficult and may even exceed the long term stability of residual magnetization of presently available magnetic shielding

Our solution to this problem is to operate at a very low spin exchange relaxation rate, which is necessary anyway to achieve the desired line Q of 10^{10}. This greatly reduces the Crampton shift. If necessary, further reduction will be accomplished by equalizing the 1,1 and the 1,-1 populations using a dc neck coil; this we have already demonstrated on our present device. The use of population mixing to reduce the Crampton effect reduces the signal by about 33%. A more elegant scheme is to use double state selection, which removes both the 1,1 and 1,-1 states [14]. Double state selection would increase the signal a factor of 3, for the same spin exchange rate, over the state mixing method and, in principle, totally eliminate the Crampton effect. This is more feasible with the passive system than in an active maser because of the reduced requirements on beam intensity. Another approach to reduce this effect is via careful centering of the storage bulb. This is difficult in a standard design because the storage bulbs are usually not perfectly symmetric. In our small dielectric cavity design the storage bulb is the inside of the dielectic shell and can be easily machined to be symmetric to better than 1%. This alone should be enough to greatly reduce the effect.

Second Order Doppler

The second order Doppler shift is 1.3×10^{-13} per degree Kelvin for atomic hydrogen. This means that the temperature needs to be stable to only 0.07 K in order to maintain an uncertainty of less than 1×10^{-14}. In our present design the temperature is stable to about 0.01 K per day, using only the outside oven. Eventually both the inner and outer oven will be used. It appears relatively easy to obtain temperature stabilities of 0.01 K per year.

Wall Shift

The wall shift is about 3×10^{-11} for a 15 cm bulb. H. Peters [15] has shown that the wall shift is at least stable to parts in 10^{13} per year. Only further work using better time scales which should include hydrogen standards will reveal the time stability of this shift. The measurements of Crampton [16] on spin exchange indicate that shifts due to paramagnetic gasses in the bulb region could be very important. As a consequence the stability of the wall shift may be influenced by cleanliness and by the stability of the background pressure. Preparation of the storage bulb prior to coating, coating material, method of coating, and even bulb operating temperature may also be important at the 1×10^{-14} level. Much work remains to be done in this area for all types of hydrogen storage devices.

Spin Exchange

The presence of appreciable hydrogen density in the storage bulb, which is desirable for strong signals, causes a frequency broadening and shift because the hyperfine frequency is perturbed during collisions. The spin exchange contribution to the linewidth is typically a fraction of a Hz [17] and uncompensated frequency pulling is of the order of percents of the broadening, i.e., fractionally, parts in 10^{12} for typical active maser operation.

In virtually all active maser designs, spin exchange broadening is compensated for by cavity pulling [18]. The residual frequency offset can then be substantially reduced. This spin exchange tuning requires beam intensity modulations and an auxiliary frequency standard (another H-maser had to be used to achieve excellent stability over many days [19,20]).

In our full size cavity design the spin-exchange frequency shift will be reduced to about 3×10^{-13} by a tenfold reduction in hydrogen density in the bulb. This permits a tenfold improvement in line Q which reduces cavity pulling and relaxes requirements on the servo. In order to maintain 1×10^{-14} frequency stability the hydrogen density must be stabilized to about 3%. This is presently being done by stabilizing the rf discharge power and hydrogen pressure in the discharge bulb. Additionally, we plan to monitor the amplitude of the second harmonic of the 0.1 Hz hydrogen modulation signal using it as a diagnostic tool (see next Section).

The passive maser could be spin exchange tuned via beam modulation as in a conventional maser; however, amplitude modulation of the microwave signal will accomplish virtually the same result without any beam modulation. This utilizes the dependence of hydrogen line Q on the transition probability which depends on the microwave power. Of course, this technique will require a careful elimination of amplitude to frequency conversion in the electronics.

Hydrogen Line Servo

Figure 6 shows that the signal from the 5 MHz local oscillator is not only phase modulated at 12.5 KHz but also at a low frequency of about 0.1 Hz. This causes the 1420 MHz carrier to be phase modulated at 0.1 Hz. After interacting with the hydrogen atoms in the cavity, the 1420 MHz signal contains amplitude modulation at 0.1 Hz with the intensity and sign determined by the frequency difference between the injected signal and the resonance frequency of the hydrogen atoms. The amplitude modulation is detected after heterodyning the 1420 MHz signal to 20 MHz and passing it through a narrow band filter in order to preserve signal-to-noise. A synchronous detector converts this signal into a dc voltage for correcting the frequency of the local oscillator. Dispersion effects in the rest of the electronics are negligibly small over a band of 0.1 Hz.

Preliminary measurements with a 15 cm bulb with a linewidth of approximately 3 Hz and a cavity of 40,000 yield a one second stability of 8×10^{-12} which improves as the square root of time at least out to 1800 seconds. These measurements are very important because with a linewidth of 3 Hz, the standard is 10 to 20 times more sensitive to most systematic effects than our new system presently under construction. It will feature a cylindrical bulb of 18 cm diameter and 20 cm height. Tests of this bulb in a different maser yield an increase in line Q of nearly 10 and a signal-to-noise about 10 times larger than presently achieved (see Fig. 9).

We therefore expect to achieve a short term stability of $\sigma_y(\tau) \leq 1 \times 10^{-12} \tau^{-1/2}$. These results coupled with measurements reported above on the reduction of cavity pulling, indicate that the full size passive hydrogen maser just described is capable of achieving a frequency stability of better than 1×10^{-14} from 1 day to perhaps a year.

We also believe that it is possible to achieve stabilities very close to this level in a passive maser measuring approximately 16" in diameter and 30" long using the small dielectric cavity.

Also it should be noted that the ability to reduce cavity pulling independently to 1×10^{-14}, to be spin exchanged tuned via microwave amplitude modulation as well as beam intensity modulation, and the ability to operate over more than an order of magnitude change in hydrogen density makes the passive masser a powerful tool for investigating systematic effects and physical processes.

REFERENCES

1. D. W. Allan, H. Hellwig, D. J. Glaze, Metrologia 11, 133 (1975).
2. Bureau International de l'Heure, Annual Report, Paris, published annually.
3. F. E. Butterfield, Proc. 30th Annual Freq. Control Symp., Ft. Monmouth, NJ (1976) to be published.
4. K. Kleppner, H. C. Berg, S. B. Crampton, N. F. Ramsey, R. F. C. Vessot, H. E. Peters, J. Vanier, Phys. Rev., 138, A972 (1965).
5. R. F. C. Vessot, M. W. Levine, P.W. Zizewitz, P. Debely, N. F. Ramsey, Proc. Int. Conf. on Prec. Meas. and Fund. Const., National Bureau of Standards Special Publ. No. 343, 27 (1970).
6. H. Hellwig, Metrologia 6, 56 (1970).
7. H. Hellwig, H. Bell, Metrologia 8, 96 (1972).
8. H. Hellwig, H. Bell, Proc. 26th Annual Freq. Control Symp., Ft. Monmouth, NJ, 242 (1972).
9. H. E. Peters, Proc. 26th Annual Freq. Control Symp., Ft. Monmouth, NJ, 230 (1972).
10. S. B. Crampton, H. T. M. Wang, Proc. 28th Annual Freq. Control Symp., Ft. Monmouth, NJ, 355 (1974).
11. J. Viennet, C. Audoin, M. Desaintfuscien, Proc. 25th Annual Freq. Control Symp., Ft. Monmouth, NJ, 337 (1971).

12. R. F. C. Vessot, M. W. Levine, Metrologia 6, 116 (1970).

13. R. F. C. Vessot, M. W. Levine, Proc. 28th Annual Freq. Control Symp., Ft. Monmouth, NJ, 408 (1974).

14. C. Audoin, M. Desaintfuscien, P. Piejus, J. P. Schermann, Proc. 23rd Annual Freq. Control Symp., Ft. Monmouth, NJ, 288 (1969).

15. H. E. Peters, D. B. Percival, Proc. 4th PTTI Meeting, Washington, DC., 55 (1972).

16. S. B. Crampton, H.T. M. Wang, Phys. Rev. A 12, 1305 (1975).

17. P. L. Bender, Phys. Rev. 132, 2154 (1963).

18. S. B. Crampton, Ph.D. Thesis, Harvard University, 1964, unpublished. See also J. Vanier, R. F. C. Vessot, Appl. Phys. Letters 4, 122 (1964).

19. O. Gheorghiu, J. Viennet, P. Petit, C. Audoin: C. R. Acad. Sc. Paris 278, Series B, 1059 (1974).

20. D. Morris, K. Nakagiri, Metrologia 12, 1 (1976).

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*This work was supported by the Naval Research Laboratory, Contract #N00173-75-F-D-046.

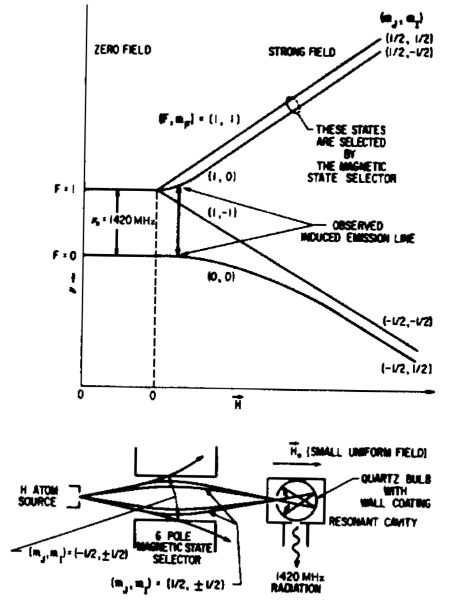

Fig. 1 Top Atomic hydrogen hyperfine ground state energy levels in an applied magnetic field.

Bottom Schematic of system typically used to create and state select atomic hydrogen for use in hydrogen frequency standards.

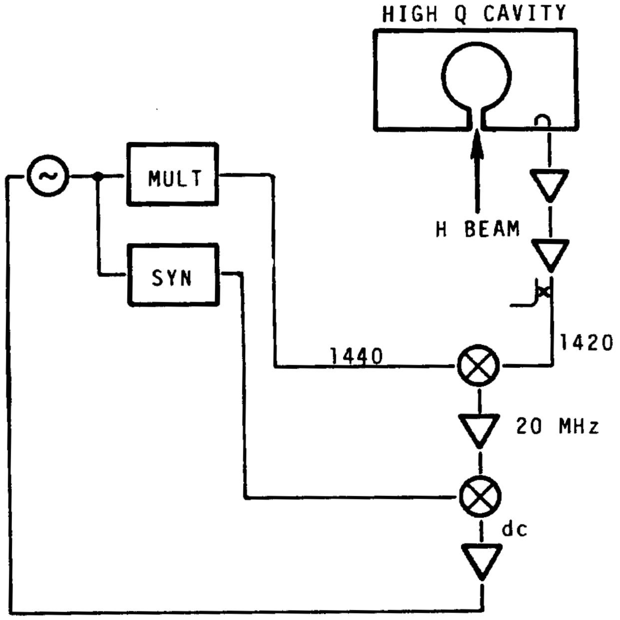

Fig. 2 Simplified block diagram of an active hydrogen maser frequency standard.

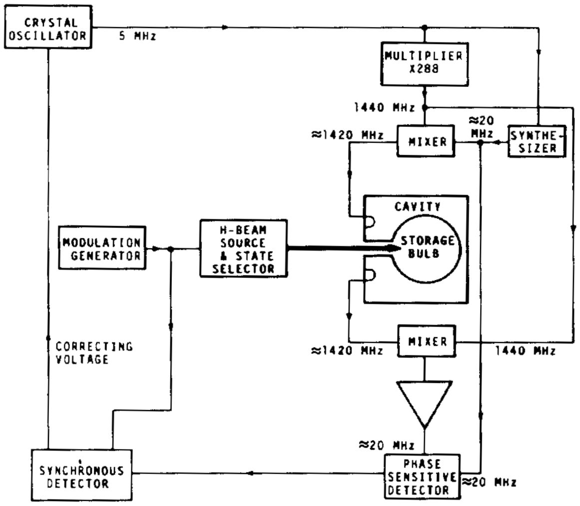

Fig. 3 Simplified block diagram of passive hydrogen maser frequency standard using dispersion locking [6,7].

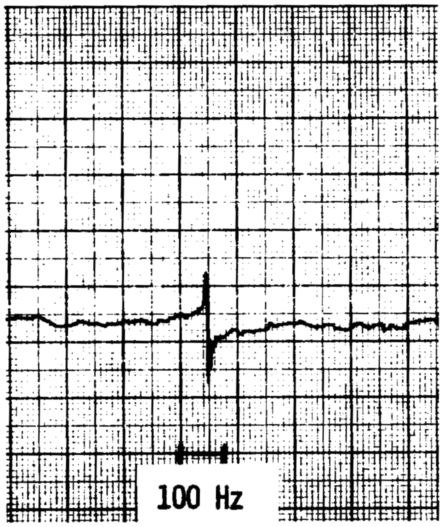

Fig. 4 Dispersion signal appearing at the output of the 20 MHz phase sensitive detector of Fig. 3 as the interrogation frequency is swept through the hydrogen resonance.

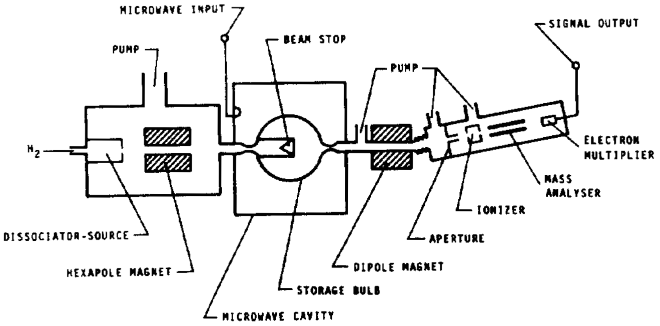

Fig. 5 Schematic of the hydrogen beam storage device [8].

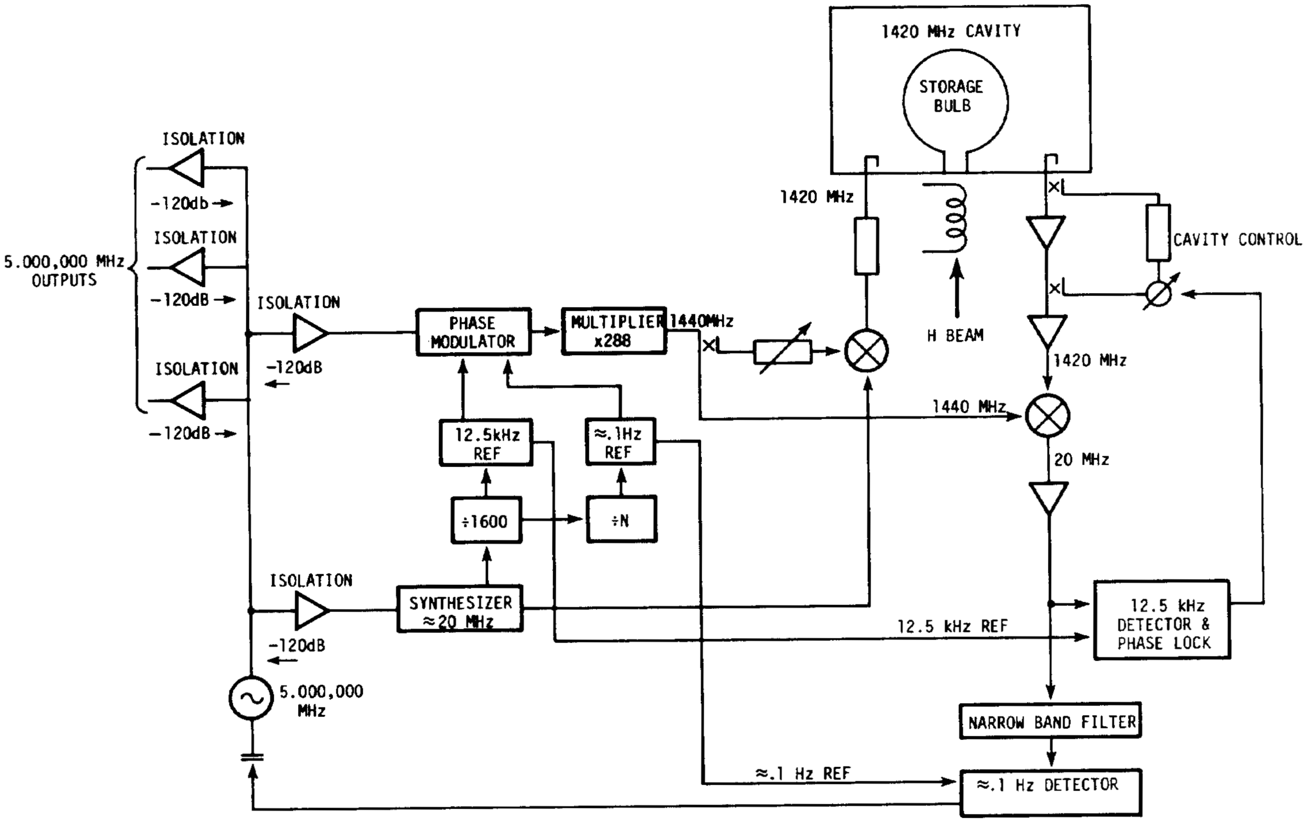

Fig. 6 Block diagram of our present passive hydrogen maser frequency standard.

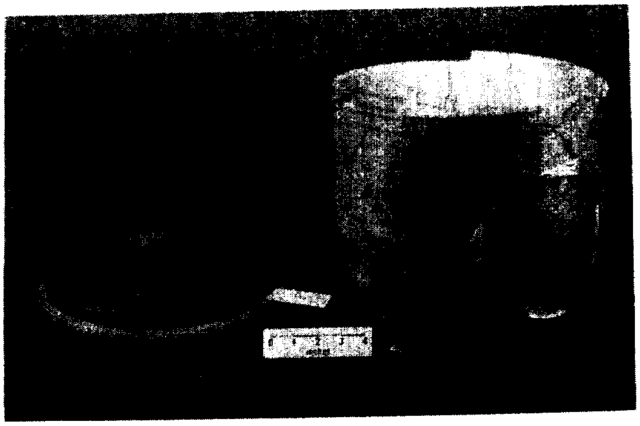

Fig. 7 Photograph of small TE_{011} dielectric cavity along side a model full sized TE_{011} 1420 MHz cavity. Barrel of actual cavity is quartz and ends are aluminum.

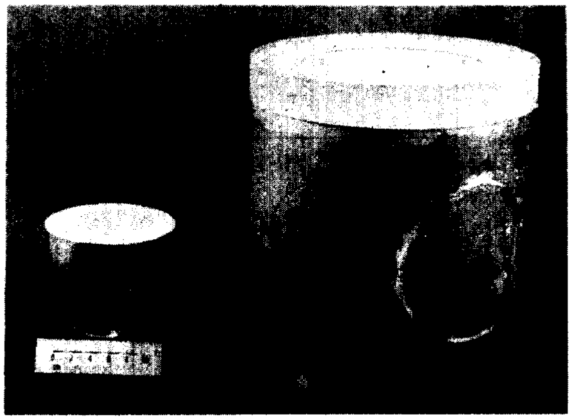

Fig. 8 Barrel and top end cap of full sized TE_{011} 1420 MHz cavity. Cavity length is adjusted by rotating the barrel. See Fig. 7. Note choke on top flange which is used to separate and suppress the TM cavity modes.

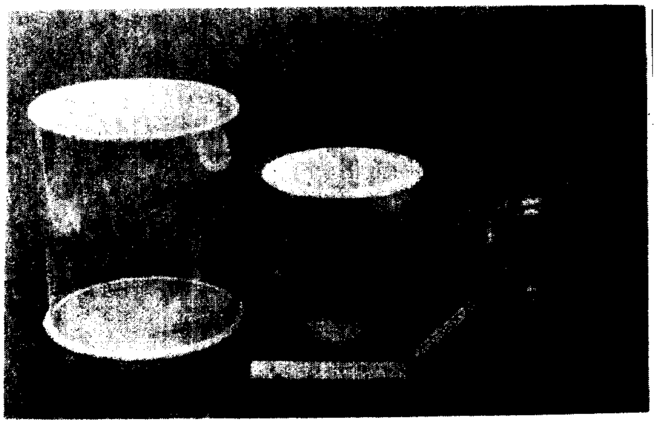

Fig. 9 (left to right) Photograph of 18 cm dia. x 20 cm high storage bulb, dielectric cavity, and 15 cm dia. storage bulb.