A New Miniaturized Passive Hydrogen Maser

F. L. Walls and K. B. Persson
National Bureau of Standards
Time and Frequency Division
Boulder, Colorado 80303

ABSTRACT

The small passive hydrogen maser design developed at NBS has been further refined to produce a much smaller device with enhanced performance. This new miniaturized passive hydrogen maser is rack mounted, measuring 26 1/2 cm high exclusive of its external power supply. The weight is ~ 30 kg with a steady state power consumption of about 54 W at 25°C. The reduction in the size and power has been achieved primarily by major changes in the beam optics, offset frequency synthesizer, and hydrogen supply. The present size is small enough to fit in the NBS environmental chamber used to house commercial cesium frequency standards.

Long-term measurements against the NBS time scale indicate that the new miniature passive maser (MPH) design has a timekeeping ability over at least a few weeks which is better than our entire ensemble of 14 commercial cesium clocks. Frequency measurements vs the time scale (TA NBS) over the last 50 days yield a joint frequency stability of $4.7^{+1.3}_{-3.6} \times 10^{-15}$ at 10 days. Preliminary analysis indicates that the cesium ensemble is the major contributor to this value. Extrapolation of the 1 day frequency stability sets a lower limit of 1.5×10^{-15} at 10 days for maser MPH 14 at its present flux level. Using a linear least squared fit to frequency drift between MPH 14 and the cesium ensemble yields a value of $2 \pm 5 \times 10^{-16}$/day averaged over 50 days. The net result is that this new generation of miniature hydrogen clocks can keep time to a few nanoseconds per week.

INTRODUCTION

For many years precision timekeeping has relied nearly exclusively on commercially available cesium beam standards with a nominal fractional frequency stability of order 3×10^{-14} at one day and a timekeeping performance of order 20 ns per week. In this paper we describe a new generation of miniature passive hydrogen masers (MPH) developed at NBS, which are comparable in size, weight, and power to the commercially available cesium standards. The new MPH standards, however, have a frequency stability and timekeeping ability which is far superior to any presently available commercial cesium device.

The small hydrogen maser design (SPHM) previously developed at NBS [1-3] demonstrated excellent frequency stability, however it wasn't very portable. Typical fractional frequency stability was $2 \times 10^{-12}\ t^{-1/2}$ out to about one week. Frequency drift vs the NBS cesium ensemble was not significant compared to the measurement noise of $\pm 5 \times 10^{-16}$/day. The design of this early passive maser was nearly 1.5 m (5 feet) tall and weighed about 90 kg (200 pounds).

The new generation of miniature passive hydrogen maser (MPH) just now being completed at NBS exhibits excellent frequency stability and is much, much, smaller than the SPHM design. The current MPH design is 26.7 cm tall, 66 cm deep, and 49.5 cm wide (standard relay rack width) . This rack mounted device weighs 30 kg (65 pounds) exclusive of its ac power supply and uses 54 watts of power at 25°C. Fractional frequency stability at one day is about 7×10^{-15} and the timekeeping ability exceeds 4 ns a week.

PASSIVE HYDROGEN MASER BEAM ADVANCES

Several years ago NBS embarked on a program to develop a frequency standard based on the hydrogen magnetic hyperfine resonance shown in Figure 1. The basic technique for state preparation was virtually unchanged from earlier active hydrogen maser work utilizing hexapole magnets [4]. The length of the beam path from the source to the storage bottle in the previous design was 43 cm (17 inches), largely dictated by the focusing/defocusing characteristics of the hexapole magnet. By going to a quadrupole magnet with an inlet bore of 0.05 cm (0.020 inches), it was possible to reduce the beam length to slightly over 10 cm. This is due solely to the large deflection angles of the unwanted atoms achieved with quadrupole magnets [5]. This greatly shortened beam optics then made it possible to make the beam horizontal and still fit in a standard rack mount.

Measurements on the sensitivity of the output frequency of the earlier SPHM series on applied external magnetic field showed a quadratic dependence of order 1×10^{-13} for $\pm 3 \times 10^{-5}$T (±0.3 G) change. The quadratic behavior and the fact that the value was much larger than that expected from measurements on the Zeeman shifts, indicated that there was a significant magnetic field inhomogenity shift (Crampton Effect [6]). Both the SPHM and MPH series use four magnetic shields separated by about 1.2 cm with an overall Zeeman shielding coefficient of about 200,000 along the beam axis. With the greatly shortened beam optics of the MPH series, it was relatively easy to extend the outer magnetic cover in order to partially shield the discharge bulb and the entire beam optics from changes in the external magnetic field. Figure 2 shows the measured shifts in output frequency of the maser due to changes of the external magnetic field. The shifts are still quadratic in nature but of much lower level, indicating that further shielding in this area would probably help reduce this effect even more. Nevertheless, the present performance of 2×10^{-15} for $\pm 1.5 \times 10^{-5}$T (±0.15 G) is more than adequate for operation in benign laboratory environments.

The storage cavity for both the older SPHM and the new MPH series uses a right circular cylinder of low-loss Al_2O_3 ceramic with a bore down the central axis and a silver coating on the outside. The ends are capped with Al_2O_3 plates. The closed central bore is coated with FEP 120 teflon*. Thus, this dielectrically coated cavity serves as the microwave cavity, the vacuum chamber, and the storage volume. The integral nature of this design makes it very rugged. An additional feature is that the Al_2O_3 is a very good thermal conductor thereby greatly reducing temperature gradients along the storage volume. This feature has made it possible to use only a single oven for control

*Certain commercial materials are identified in this paper in order to adequately specify the experimental procedure. Such identification does not imply recommendation or endorsement by the National Bureau of Standards, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

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of the cavity frequency for applications with a benign thermal environment. Two ovens will probably be required for use under field conditions. Long term temperature coefficients are less than 3 x 10^{-14}/K. Additional analysis of this effect is planned over the next several months.

SERVO SYSTEMS

In the approach developed at NBS, both the output oscillator and the microwave cavity are locked to the hydrogen resonance using the scheme illustrated in Figure 3 [1-3]. Briefly, a local probe signal ultimately derived from 5 MHz is phase modulated at two frequencies, f_1 and f_2, and introduced into the microwave cavity containing the state-selected hydrogen atoms. The transmitter signal is envelope-detected and processed in two synchronous detectors, one referenced to the modulation frequency, f_1, and the other to f_2. f_1 corresponds to approximately the half-linewidth of the microwave cavity and f_2 corresponds to the half-linewidth of the hydrogen resonance. The output of the f_1 synchronous detector is used to actively correct the microwave cavity frequency with a time constant of about 10 seconds. The output of the f_2 synchronous detector is used to steer the probe frequency to the center of the hydrogen line with a time constant of several seconds. The unique feature of the passive hydrogen masers, as compared to the active hydrogen masers, is the ability to lock the microwave cavity frequency to the hydrogen resonance frequency without the need for an external high-stability reference. Lesage et al., have theoretically examined the expected characteristics of such a system [7]. Their results agree rather well with the experimentally observed characteristics. Recent work by Peters in these proceedings show first results of a cavity switching servo.

SYSTEMATIC EFFECTS

Systematic effects which can perturb the output frequency are listed in Table 1 with the expected effect on stability. The temperature coefficient shown is an upper bound as the thermal response hasn't been carefully analyzed over the long times necessary to obtain a precision of parts in 10^{15}.

Several masers of the SPHM series which were let up to air for servicing and repumped, recovered frequency to 2 x 10^{-13} or better. Adjustments on the electronics of MPH 14 showed shifts of order 1 x 10^{-13}. The results on both the SPHM and the first of the MPH masers indicate that the drift is extremely small (less than 5 x 10^{-16}/day) therefore changes in the wall shift are probably negligible. Therefore it is expected that the reproducibility after servicing of virtually any component, save replacing the cavity, will be better than 3 x 10^{-13}.

Table 1. Summary of Systematic Effects for the Miniature Passive Hydrogen Maser.

EFFECT	OFFSET	INSTABILITY
1. Second-order Doppler Changes	-4.3×10^{-11}	3×10^{-15}
2. Cavity Pulling and Temperature Coefficient		$\leq 3 \times 10^{-14}$/K
3. Wall Shift	$- 2 \times 10^{-11}$	$\leq 10^{-13}$/year
4. Spin Exchange	2×10^{-13}	5×10^{-15}
5. Magnetic Field Changes	$+2 \times 10^{-15}$ for $\pm 1.5 \times 10^{-5}$ T ($\pm$0.15G)	10^{-15}
6. Power Dependence	$< 10^{-13}$/dB	10^{-15}
7. Phase Modulator Drive	$< 10^{-13}$/dB	10^{-15}

FREQUENCY STABILITY AND TIMEKEEPING RESULTS

The frequency stability and timekeeping capability of the first of the new series of miniature passive masers, MPH 14, has been analyzed over the past 50 days vs the NBS ensemble of cesium clocks. Figure 4 shows the measured fractional frequency stability vs TA NBS. This time scale is post analyzed monthly and defective clocks are removed. Three corner hat analysis (comparisons between three clocks) out to 1 day shows that a major portion of the instability in the data is attributable to the cesium ensemble. MPH 14 is a part of the ensemble and carries a weight of approximately 24%. The actual weight varies as various clocks are added or removed from the ensemble.

Figure 5 shows the timekeeping performance of MPH 14 vs TA NBS over the past 50 days. This data is particularly remarkable because the power to the maser was off for a short time on MJD 45801 (day 6) and 45814 (day 19). The time scale computer reset the phase after each power outage but didn't adjust frequency. MPH 14 recovered frequency to within several parts in 10^{15} after each outage. Figure 6a shows the timing between MPH 14 and AT1 NBS over a two week period. For comparison the timing performance of a "very good" high performance commercial cesium beam standard over the same time is shown in Figure 6b. The on-line time scale AT1 is slightly smoother than TA NBS in short-term.

Based on the above data, the time dispersion between MPH 14 and NBS time scale varies from 0.9 ns for a prediction interval of one day, to 4 ns at a prediction interval of 7 days.

Most of the time dispersion appears to be due to the noise in the ensemble of cesium standards comprising TA NBS. Nevertheless, we can determine that the performance of MPH 14 is more than a factor of 3 times better than the best commercially available cesium standard for measurement times out to at least several weeks. (Three corner hat data suggests that MPH 14 is 5 times better than the best commercial cesium at 1 day.)

The data of Figure 5 was analyzed for frequency drift. The computed drift of 2 x 10^{-16}/day is much less than the uncertainty of ± 5 x 10^{-16} due to noise in the cesium ensemble.

CONCLUSION

It has been experimentally demonstrated that the MPH design yields a relatively small clock quite comparable in size, weight, and power to commercial cesium devices but capable of much better performance. The timekeeping of this new design of passive hydrogen maser exceeds 4 ns/week and may be as good as 1.5 ns/week (measurements are limited by instabilities in the cesium clocks used for the reference). Frequency drift is so small as to be hidden within the noise of the cesium ensemble even when averaged over 50 days.

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Figure Captions

Figure 1. Upper portion shows the magnetic hyperfine separation of atomic hydrogen vs magnetic field. The lower portion shows the traditional method of state selection using a hexapole magnet.

Figure 2. Change in output frequency of MPH-14 vs externally applied magnetic field. The broken lines are only to help guide the eye.

Figure 3. Block Diagram of the electronic servo concept used in the SPHM and MPH passive masers.

Figure 4. Fractional frequency stability $\sigma_y(\tau)$ of MPH-14 vs TA NBS as a function of measurement time. MPH-14 has a weight of ~ 24% in TA NBS. No correction has been applied due to the self inclusion of the clock in the time scale or due to possible frequency drift.

Figure 5. Time comparison of MPH-14 vs TA NBS over 50 days starting at MJD 45795. The average frequency difference has been subtracted from the raw data. No correction has been applied due to the self inclusion of the clock in the time scale or due to possible frequency drift. MPH-14 has a weight of 24% in TA NBS.

Figure 6a. Time comparison of MPH-14 vs AT1 NBS starting at MJD 45798. The average frequency difference has been subtracted from the data. No correction has been applied to the self inclusion of the clock in time scale or due to possible drift. MPH-14 has a weight of 18% in AT1 at the time of this data.

Figure 6b. Time dispersion of clock 12, a high performance commercial cesium beam frequency standard, vs AT1 NBS starting at MJD 45798. The average frequency difference has been subtracted from the raw data. No correction has been applied due to the self inclusion of the clock in the time scale or due to possible frequency drift. Clock 12 has a weight of 23% in AT1 at the time of this data.

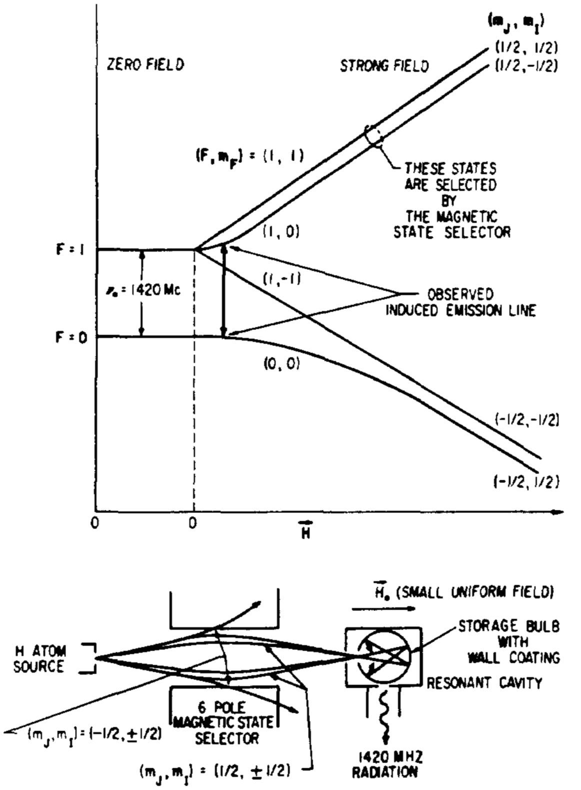

Fig. 1

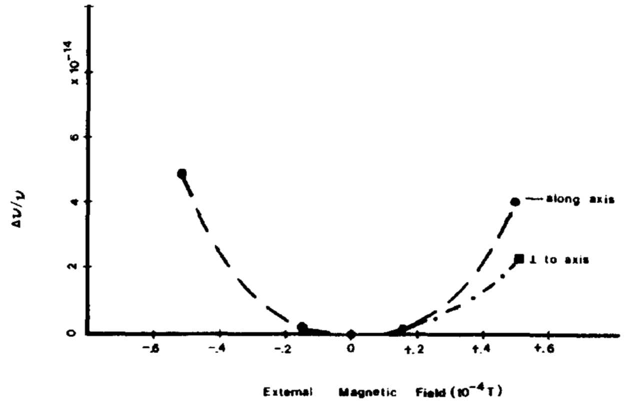

Fig. 2

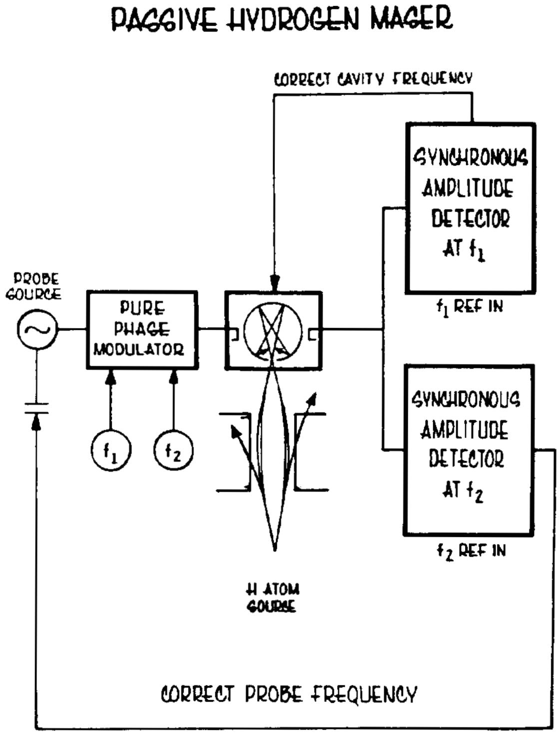

Fig. 3

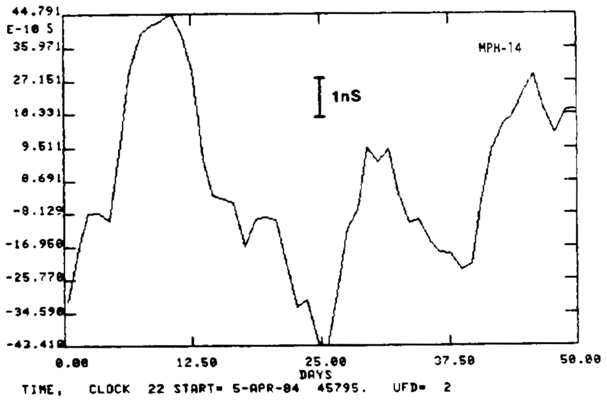

Fig. 5

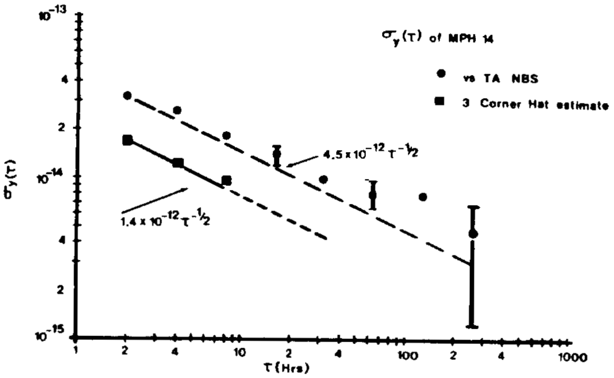

Fig. 4

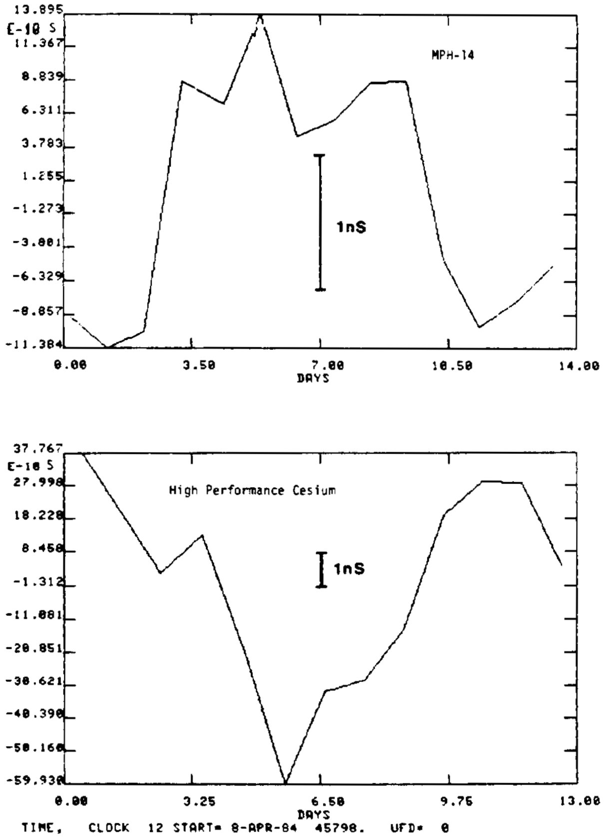

Fig. 6