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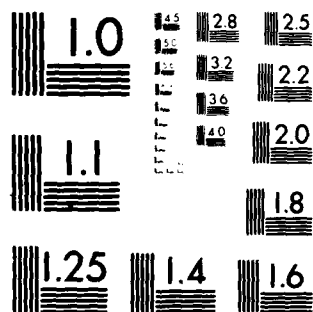
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RADC-TR-81-270
Interim Report
October 1981



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LIGHT-WEIGHT HYDROGEN MASER

Sigma Tau Standards Corporation

Harry E. Peters

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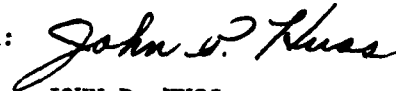
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SUMMARY

A. OBJECTIVES OF THE CONTRACT

The objectives of this contract are to develop an atomic hydrogen maser frequency and time standard which is smaller and lighter by a factor of eight or more from previous designs and which is correspondingly less expensive, but which exhibits improved stability performance over other atomic standards, as well as improved reliability, efficiency, and operating life.

B. TECHNICAL PROBLEM

Atomic hydrogen maser frequency and time standards exhibit exceptionally good stability, reproducibility, and accuracy, and are potentially useful in a wide range of critical applications. However, in the past these masers have been very large (180x50x50 cm), very heavy (200-400 Kg), and very expensive (\$100,000.00 and up). The large size has been due to the use of a large microwave cavity resonant at the hydrogen frequency, with associated vacuum system, magnetic shields, and thermal enclosure. If means for reducing the cavity size, while maintaining adequate cavity quality factor and other physical parameters, can be realized, the technological and financial benefits will be correspondingly improved. The present contract arose from an unsolicited proposal to prove out a previously conceived new method of realization of a much smaller maser cavity resonator structure.

C. GENERAL METHODOLOGY

The general approach is to first measure and evaluate a range of cavity resonator and storage bulb assemblies having the new configuration to establish the best geometrical shape and dimensions, then to design and test a breadboard model hydrogen maser, and finally to design, fabricate, evaluate, and deliver to the US Air Force one operational atomic hydrogen maser standard prototype. The period of the contract is 3 years, which started in March 1979.

D. TECHNICAL RESULTS

With 27 months of the program complete, the work is on schedule. Preliminary tests of representative cavity resonator configurations provided the guidelines for construction of a breadboard feasibility model maser. The breadboard maser tests were successfully completed, and a deliverable prototype maser was designed. The prototype maser is in the final stage of assembly, and operational tests will be performed in the near future.

E. FUTURE WORK

The next technical reporting period covers completion of the contract. After assembly, evaluation, and documentation are completed, the prototype maser will be delivered and the final report will be submitted for approval.

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I PROGRAM OVERVIEW

The new approach to atomic hydrogen maser design upon which the LIGHT WEIGHT HYDROGEN MASER DEVELOPMENT PROGRAM of the present contract rests is described in reference (1), "Small, Very Small, and Extremely Small Hydrogen Masers," by Harry E. Peters. Subsequent work in the present program has also been described in the paper (2), "New Hydrogen Maser Designs," and (3), "Feasibility of Extremely Small Hydrogen Masers," by the same author. As is widely recognized, there is a critical need for the stability properties of the hydrogen maser in many applications, such as space tracking, navigation, global positioning systems, basic time and frequency standards, geodesy, communications, and radio astronomy. Widespread use has been limited, however, due to the hydrogen maser's large size (30 Ft³), heavy weight (500-800 pounds), great cost (\$100,000.00 to \$300,000.00), and general unavailability (only government funded laboratories have constructed hydrogen masers heretofore.)

Success with the new design concept will make hydrogen masers very attractive for a number of applications now served by less adequate standards such as cesium, rubidium, or crystal oscillators. With wide spread use the cost will be reduced further, and large numbers will make it feasible for commercial sources to provide service and application support not presently available.

There are 3 basic phases to the present program. First, to make measurements of cavity and storage bulb assemblies based upon the new concepts; second, to design and test an operational laboratory breadboard maser; and third, to design, construct, test and deliver a prototype standard to the US Air Force for performance evaluation. The program phases and the time schedule were outlined in attachments 1 and 2 of the first Interim Technical Report.

II PROGRESS

At the present time 27 months of the 36 month contract period has passed, and the work is on schedule. Since the last Interim Technical Report was presented, the electronic and physical subassemblies of the deliverable prototype hydrogen maser have been assembled and final processing and assembly of the maser is nearing completion at this writing. A

description of the prototype maser and a discussion of current research results was presented at the 35th Annual Symposium on Frequency Control in a paper "Feasibility of Extremely Small Hydrogen Masers," (3). A copy of this paper is attached.

III WORK FOR THE NEXT REPORTING PERIOD

The next technical reporting period covers completion of the contract. After assembly, evaluation, and documentation are completed, the prototype maser will be delivered and the final report will be submitted for approval.

IV EQUIPMENT PURCHASES

There have been no purchases of special government owned equipment this period.

V PERSONNEL

There have been no changes in personnel. There is one person presently engaged in this effort, the principal investigator, Harry E. Peters.

VI PREVIOUS AND RELATED CONTRACTS AND PUBLICATIONS

There are no previous or related contracts. There has been one publication, Reference (3) attached, which describes work performed under this contract.

VII REFERENCES

- (1) Harry E. Peters, "Small, Very Small, and Extremely Small Hydrogen Masers," Proceedings, 32nd Annual Symposium on Frequency Control, USAERADCOM, Fort Monmouth, NJ, 1978.
- (2) Harry E. Peters, "New Hydrogen Maser Designs," Proceedings, 34th Annual Symposium on Frequency Control, USAERADCOM, Fort Monmouth, NJ, 1980.
- (3) H.E. Peters, "Feasibility of Extremely Small Hydrogen Masers," Proceedings, 35th Annual Symposium on Frequency Control, USAERADCOM, Fort Monmouth, NJ, 1981.

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FEASIBILITY OF EXTREMELY SMALL
HYDROGEN MASERS

H. E. Peters

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STANDARDS CORPORATION**

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Preprint

This report is a preprint of a paper submitted to the 35th Annual Symposium on Frequency Control, May 27-May 29, 1981. This symposium is sponsored by the U. S. Army Electronics Command, Fort Monmouth, N. J. Copies of the 1981 Proceedings may be obtained from: Electronics Industries Association, 2001 Eye St. N. W., Washington, D. C., 20006.

FEASIBILITY OF EXTREMELY SMALL HYDROGEN MASERS

H. E. Peters

Sigma Tau Standards Corporation
Tuscaloosa, Alabama

Summary

The possibility of achieving much smaller and less expensive hydrogen masers than have been built in the past was pointed out in a paper presented at this symposium in 1978.¹ Experimental work to establish the feasibility of a "Small Hydrogen Maser," with physics unit only 9.0 inches in diameter and 19.75 inches long, has since been undertaken with support of the United States Air Force,² and progress with this work was presented in a paper, "New Hydrogen Maser Designs," which was presented at the 34th Annual Symposium on Frequency Control in 1980.³

In the following sections progress with the "Small Hydrogen Maser" prototype which is currently being assembled is presented. In addition, the effect of cavity pulling on stability is discussed, and a feasible design for an "Extremely Small Hydrogen Maser," with a cavity which is only 2 inches in diameter by 4 inches long, is presented.

Key words (for information retrieval)
Hydrogen Maser, Atomic Hydrogen Standard,
Frequency Standard, Frequency Stability.

Introduction

The active hydrogen maser oscillator has exceptionally good stability for all measurement intervals longer than one second; however it has found its greatest usefulness in specialized applications at standards laboratories, tracking stations, and radio astronomy observatories due to its remarkably superior stability for the intermediate measurement intervals between one second and one day. Limited from wider applications by its high cost, large size, and heavy weight, a very significant effort has been expended at many research and development laboratories in the last few years to overcome these obstacles without degrading the stability.

The present paper reports on the progress achieved in size and weight reduction by use of a novel design wherein electrodes are mounted directly on the storage bulb. Use of a new approach for active cavity Q enhancement to achieve

oscillation is presented and the effect of cavity pulling on the maser stability is considered. At the extreme size reduction of the "Extremely Small Hydrogen Maser," the performance achievable and the corresponding size and weight benefits are considered in the last section.

Small Hydrogen Maser

Figure 1 is a picture of the "Small Hydrogen Maser" which is presently being assembled. The instrumentation, controls and electronics sub-systems have been completed. The processing of physical sub-systems such as source, storage bulb, cavity and vacuum enclosure is in progress at this writing; these fit within the blue cylinder in the center of the framework.

The electronics sub-systems have been packaged in functionally separate modules, each of which may be uncovered for operational testing without disconnection of power. They may also be removed, repaired, or replaced as units in case of malfunction. The modules on the front panel are: 1. Vac-Ion pump supply; this is a DC-DC converter which provides 3,000 volts for the pump, 2. The source pressure control module which automatically regulates hydrogen flow, 3. The receiver synthesizer; this supplies the 405 KHz reference frequency for the receiver phase lock loop - there are 11 decades of control which give a resolution of $\pm 5 \times 10^{-15}$ for the output frequencies, 4. The receiver VCO and output buffer amplifiers, 5. The receiver local oscillator multiplier and IF amplifier module, 6. The module containing the magnetic field and cavity frequency controls, 7. The instrumentation read-out module. There are 16 read-out channels which are selected by 4 binary coded switches to provide visual indication of variables on a $4 \frac{1}{2}$ decade digital panel meter.

The power supply has been placed in a module mounted at the rear of the frame. The cover may be removed for changing connections or trouble shooting without disconnecting the power. Batteries for uninterruptable standby operation are placed in a separate external battery pack. For long term operation without A-C power, a 45 A-H capacity battery is used which will last for fifteen hours.

Breadboard Maser Tests

First tests of a breadboard hydrogen maser which had cavity and bulb dimensions similar to the prototype maser presently under construction indicated that the maser did not oscillate at the hydrogen flux available. The beam was observed using pulsed stimulated emission. After optimizing the source collimator and re-aligning the beam optics, the situation was improved, but the maser still would not quite oscillate. While the breadboard maser oscillation parameters were not as ideal as might be achieved with improved techniques of bulb and cavity processing, it was decided to try a new method of cavity Q enhancement as an alternative design approach to assure efficient operation and to facilitate tests. This was successful, and using this method the breadboard maser oscillated. The effect on maser stability and the method used are discussed in the following sections.

The minimum cavity Q for oscillation was approximately 20,000, the hydrogen flux was 5×10^{-5} Torr-liter/second, and the line Q was 9×10^5 . Use of a smaller line Q in the prototype maser, and larger bulb aperture, will lower the oscillation threshold and lessen the effect of spin-exchange in reducing oscillation amplitude.

Cavity Pulling

Factors which relate to the resonant cavity surrounding the maser storage bulb are most critical in determining whether the maser will oscillate, how high the hydrogen beam flux must be, and to what extent the maser output frequency is changed by cavity pulling. If the cavity changes by an amount Δf_c , the oscillation frequency will change by an amount $\Delta f_m = (Q_c/Q_l) \Delta f_c$. Thus we would like to use a low cavity Q. However, the flux required for oscillation, as well as the spin-exchange parameter, vary as $(1/Q_c)$, so too low a cavity Q results in unreliable operation, low signal to noise ratio, a requirement for high flux, and early pump saturation. So one is forced to strike a balance between achieving a practical oscillating maser and attainment of the best long term stability.

In the small hydrogen maser, without Q enhancement, the ratio of cavity Q to line Q is approximately 1.5×10^{-5} which is comparable to the value attained in conventional large hydrogen masers. If active Q enhancement by some factor is used, the maser will be that much more sensitive to cavity frequency changes. Also, depending upon the technique used, there may be severe electronic or environmental perturbations of the maser output frequency.

While it is clearly desirable to minimize the amount of Q enhancement used, the small ratio of Q_c to Q_l , as well as the low cavity thermal coefficient, permits Q_c to be raised significantly

while still maintaining good long term stability, providing some of the problems inherent in previous attempts to use Q enhancement can be avoided.

Active Cavity Q Enhancement

Figure 2 illustrates two approaches to hydrogen maser cavity Q enhancement. Figure 2a illustrates the methods described in references (4) and (5). Two coupling loops are used and coaxial cable connects these to a variable gain amplifier, a band-pass filter, and a phase matching circuit so that a signal of proper amplitude and phase is returned to the cavity to reduce the losses. The amplifier, filter, phase matching network, and coaxial connections are outside the thermally controlled and shielded region of the maser cavity. The inherent mechanical, thermal, and electronic perturbations inherent in this method introduce unacceptable frequency perturbations for use as a standard. Wang⁵ has added a cavity stabilization servo to avoid these problems, however, this entails additional complexity, as well as new perturbations.

Figure 2b illustrates the method developed for use in the small hydrogen maser. In this case, a transistor amplifier is coupled directly to a single loop within the maser cavity. The phase and gain parameters are adjusted by varying the bias voltage. The circuit is mounted on the cavity adjacent to the magnetic shield. Using swept frequency methods, the enhanced cavity resonance is measured just as in a conventional maser cavity without gain. The signal is detected through a separate, independent, loop using very light coupling. It should be emphasized that the only real difference between these two figures is that there are no RF components, other than the output connection, outside the maser inner magnetic shield in Figure 2b. Thus one may achieve the degree of thermal and mechanical stability typical of a single cavity structure.

Extremely Small Hydrogen Maser

If active cavity Q enhancement is to be used, the usual restrictions on cavity size are greatly reduced. In fact, by reducing cavity size, one of the most difficult problems can be eliminated. In a large cavity there are numerous high Q resonant modes. To avoid spurious oscillations one must couple only to the proper mode, or assure that the gain at extraneous resonance frequencies is small. This can be accomplished by a band-pass filter in the conventional method of figure 2a, or by proper configuration of the cavity and judicious orientation of the coupling loop in the method of figure 2b.

A much better way is to make the cavity small enough that the only mode within the band-pass of the cavity amplifier is the one desired at the hydrogen frequency. A cavity 4 inches long by 2 inches diameter, with bulb 1 inch in diameter having electrodes configured as in reference (1).

may be made resonant in the proper mode, and extraneous resonances are an octave or more higher in frequency. A test cavity of copper, with a quartz tube, which closely approximated the desired physical shape and electrical parameters, has been measured. The loaded Q ranged from 5,000 with no active gain, to over 50,000 with gain, and could be controlled by bias voltage variation within this range. There were no other resonances within the 1,800 MHz maximum frequency of the instrumentation.

The line Q of a maser with a one inch diameter bulb would be about 4×10^5 , extrapolating from the 2 inch diameter bulb of the SHM or the 5 inch diameter bulb typical of large hydrogen masers. With an enhanced cavity Q of 24,000, the pulling factor is only 6×10^{-5} . The threshold for oscillation will go down directly as the bulb diameter, so less hydrogen flux will be required. The spin exchange parameter will remain essentially unchanged from that of larger masers. Of course, the intrinsic accuracy will be about a factor of 5 worse than that of large hydrogen masers, so use as a fundamental standard is not anticipated, but where the requirement is for exceptional stability for periods up to a few days or a few weeks, the ESHM may be very useful.

Figure 3 is a drawing which illustrates the remarkable size reduction that may be accomplished. This shows the "physics package" of a design which is only 5 inches in diameter and 10 inches in length. This is also, most likely, the smallest practical size, since the source assembly is about the size of the cavity, and may not be reduced significantly without encountering dissociator problems. The pump and the required electronics are also comparable in weight and size to the physics package, thus there is little motivation to further reduce the physics package size.

Stability Goals

Figure 4 illustrates the stability goals for the "Extremely Small Hydrogen Maser," as well as the expected performance of the "Small Hydrogen Maser." For reference, the stability currently realized with typical good conventional large hydrogen masers is shown.

Though the stability of the SHM (or the ESHM) has not yet been measured, there is a good basis for predicting what it should be if we achieve cavity stability similar to that which is obtained with analogous electro-mechanical oscillators under optimum environmental conditions. It should be emphasized that the hydrogen maser may be viewed as a device which improves upon the stability of a cavity resonator by the ratio of line Q to cavity Q - typically about a factor of 10^5 .

Theoretical noise limits do not provide a good basis for estimating the stability of a gain-enhanced cavity system because long term

systematic variables or the degree of environmental isolation achieved are the predominant considerations. Consideration of the performance of devices such as super-conducting cavity stabilized oscillators, or crystal oscillators, which depend directly on gross physical dimensions just as a microwave cavity does, give a very optimistic view of the stability potential for a maser with enhanced cavity Q . For example, improvement by a factor of 6×10^{-5} over the stability of a very good crystal oscillator would give stabilities in the 10^{-17} range (other limits, such as perturbing noise or additive noise, would actually be encountered before this level is achieved.)

Thus the simple addition of an amplifier in a cavity loop does not inherently make the system unstable in frequency. There is, therefore, a very good basis for predicting the stabilities illustrated in figure 4 for the "Extremely Small Hydrogen Maser" as well as for the "Small Hydrogen Maser."

Conclusion

The work reported herein has been undertaken to demonstrate that the excellent stability properties of a good hydrogen maser may be achieved with practical masers which are an order of magnitude smaller and lighter than the conventional large maser. The present results and considerations provide an excellent basis for confidence that this goal may be attained.

References

1. Harry E. Peters, "Small, Very Small, and Extremely Small Hydrogen Masers," Proceedings, 32nd Annual Symposium on Frequency Control, USAERADCOM, Fort Monmouth, NJ, 1978.
2. This work is supported by the U.S. Air Force, RADC(ET), Deputy for Electronic Technology, Hanscom AFB, MA.
3. H.E. Peters, "New Hydrogen Maser Designs," Proceedings, 34th Annual Symposium on Frequency Control, USAERADCOM, Fort Monmouth, NJ, 1980.
4. C. Adoin, M. Desaintfuscien, and J.P. Schermann, "Application of The Transient Behavior to The Hydrogen Maser," Proceedings, 22nd Annual Symposium of Frequency Control, U.S. Army Electronics Command, Fort Monmouth, NJ, 1968.
5. H.T.M. Wang, "An Oscillating Compact Hydrogen Maser," Proceedings, 34th Annual Symposium on Frequency Control, USAERADCOM, Fort Monmouth, NJ, 1980.

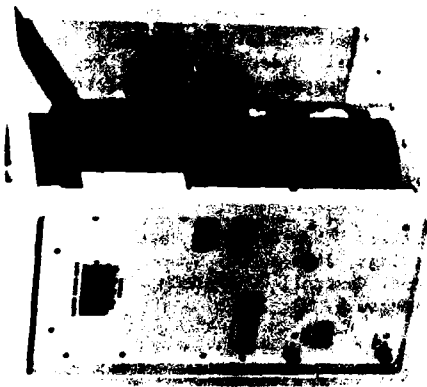


Figure 1. Small Hydrogen Maser.

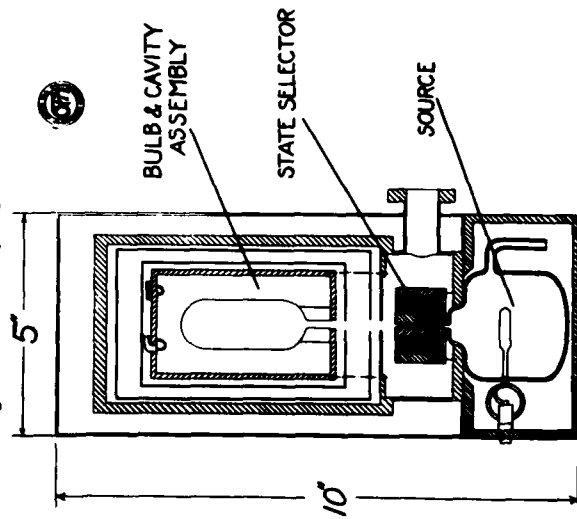


Figure 3. Extremely Small Hydrogen Maser.

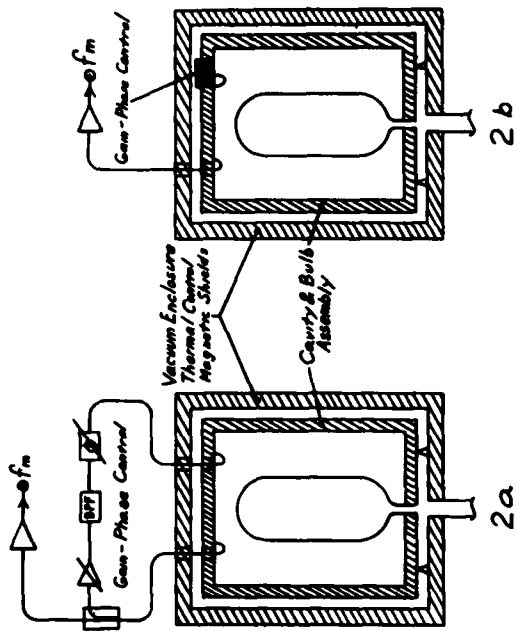


Figure 2. Cavity Active Q Enhancement Methods.

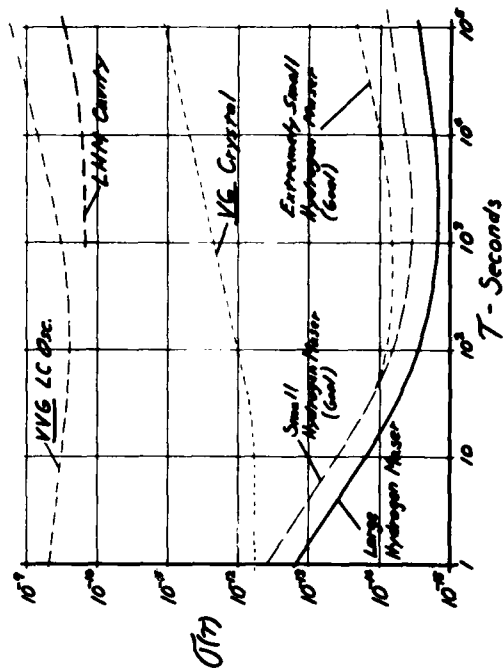


Figure 4. Stability Goals.

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