A SMALL, PASSIVELY OPERATED HYDROGEN MASER

D. A. Howe, F. L. Walls, Howard E. Bell, and Helmut Hellwig

Frequency and Time Standards Group
National Bureau of Standards
Boulder, CO 80303

Abstract

A compact passive hydrogen maser with many unique features, including a significant reduction in size over previous hydrogen masers, is described. It uses the passive mode of operation, thereby permitting use of a small microwave TE_{011} cavity which is dielectrically loaded by a low-loss alumina (Al_2O_3). The cavity is 14.6 cm O.D. and 13.7 cm high, weighing only 4.4 kg. The unloaded cavity Q factor is about 6000. With a conventional source, hexapole state selector, and 4 magnetic shields the volume of the entire H-maser resonator package is only about 20 ℓ.

The teflon coated quartz bulb which is common in other masers has been replaced by a teflon coating on the inside wall of the cavity. This has yielded a simpler design and more rugged H-maser package. The technique for the application of liquid emulsion FEP 120 is discussed.

The cavity and attached endcaps comprise the vacuum envelope, thus allowing use of a single vacuum system. The dimensional stability of the ceramic cavity under barometric changes is sufficiently within the range of the electronic cavity servo that a second vacuum system is not needed. For temperature control, a single oven is located in the magnetic shield nest.

The electronics for this small passive hydrogen maser is very similar to that previously developed at NBS. Preliminary measurements on a prototype small maser system yield a frequency stability of approximately $\sigma_y(\tau) = 6.6 \times 10^{-12}\ \tau^{-\frac{1}{2}}$ to at least one day, with a measurement bandwidth of 1 kHz.

Introduction

The construction details of a small, passively operated hydrogen maser are presented. The concept of the passive maser was introduced in order to obtain better long term stability than that seen using active maser designs.[1,2,3] A quartz oscillator is locked to the hyperfine resonance using a design reminiscent of optical pumping and atomic and molecular beam devices. Two important requirements of conventional oscillating masers have been relaxed: (1) A relatively high cavity Q (needed for oscillation), (2) excellent cavity frequency stability as a function of temperature, pressure, voltage, and time. The second point is possible because in the passive mode of operation one has the ability to lock the frequency of the cavity to the H resonance. Passive electronics has been successfully deployed on a conventional full size maser.[1,2,3] The development of this new electronics makes possible a reevaluation of the design parameters used in the maser (the so-called "physics package").

The maser works on the magnetic dipole transition of the ground state of free hydrogen atoms contained in a storage volume. Figure 1 shows the F = 0 and F = 1 states as a function of applied magnetic field. This hyperfine transition in hydrogen has a frequency of 1420405751.77 Hz. RF interrogation of the hydrogen atoms at this frequency takes place within a teflon coated storage volume. This wall-coating typically permits the hydrogen atoms to bounce 2×10^4 times within this volume before loosing their phase relative to the RF magnetic field.

In order to achieve high filling factors the instantaneous RF magnetic field needs to be singly directed over the entire hydrogen storage volume.[4] With the use of low loss alumina dielectric material, one can develop cavity designs which yield small size and relatively high filling factor over a given volume. The cavity design used here is a right circular cylinder of low-loss ceramic with a bore down the central axis and a silver jacket on the outside surface. The ends are capped with Al_2O_3 plates. The closed central bore is the hydrogen storage volume. Along with good filling factor this geometry has the benefit of good symmetry about all axes of the RF magnetic field in the storage volume. The TE_{011} mode is used. In this new design the microwave cavity therefore forms the vacuum envelope and storage volume. With currently available dielectric materials this is only made possible because of the passive electronic scheme.

Passive Maser Electronics

Figure 2 shows a block diagram of the electronics used in previous work with a full size hydrogen maser. The same scheme was deployed in the small maser described here. A thorough explanation of the operation of the servo system is described in references 1, 2, and 3. The interrogation (exciter) signal at 1420 MHz which enters the cavity is phase modulated at two frequencies, f1 and f2. Frequency f1 is a high frequency (12 kHz) phase modulation component used to probe the hydrogen cavity. Modulation component f2 is used to probe the hydrogen resonance. Figure 3 shows the spectrum of the exciter signal. This FM spectrum, after going through the cavity, then contains amplitude modulation components at frequencies f1 and f2. The transmitted microwave signal is envelope detected to recover f1 and f2 amplitude modulation components. Phase sensitive (synchronous) detectors are referenced to f1 and f2 and are used respectively to (1) determine the cavity frequency relative to the probe frequency, and (2) determine the probe frequency relative to the narrow hydrogen resonance. First, a correction signal is applied to the quartz oscillator which generates the probe frequency so that it is centered on the hydrogen resonance. Second, the cavity is tuned so that it is centered symmetrically about the probe frequency.

Concept of the Dielectrically Loaded Cavity

Figure 4 shows a development sequence of the small cavity design. Most masers use a conventional TE_{011} mode microwave cavity with approximately a diameter of 21 cm and a length of about 50 cm. The lumped constant equivalent circuit for such a cavity consists of an inductance L in series with a capacitance C in series with a resistance R. The insertion of a dielectric which affects the propagation constant ε will increase C, thus decreasing the frequency of the cavity. The overall dimension of the cavity can then be reduced to compensate for the added dielectric. Symmetry, dielectric constant, overall dimension and filling factor are then traded against each other to achieve a given geometry. The effect of the frequency of the TE_{011} mode needs to be factored into the design at this stage. Solving for the frequency requires the solution to a boundary value problem involving a differential equation describing the electromagnetic propagation within the cavity. The dielectric loading of the cavity affects the electric field; the RF magnetic field (which excites the atoms) is pinned to the defined orientation of the electric fields within the cavity. It is possible to choose a cavity bore diameter so that the oscillating axial H-field does not reverse sign in this region. Consequently, the inside bore can substitute for the conventional storage bulb with little compromise in the filling factor.

Details of the Fabrication of the Cavity

The small hydrogen maser uses a ceramic cavity (Al_2O_3) of AD-99.5 which has a loss tangent less than 10^{-4}. Using a silver coat which is fired on the outside surface of cavities cut to 1.42 GHz has yielded unloaded Q's of typically 6,000. The silver solution used is Englehard Industries' #A-2405.[5] This solution consists of silver suspended with a glass frit in a binder solution. The entire solution is first thinned with 1½ cm^3 toluene to 5 grams of A-2405. This mixture is stirred and immediately loaded into a miniature spray gun. This solution is sprayed directly on the cylinder outside surface until a black matte finish is achieved. The solution is allowed to dry for 10 minutes, after which time the coated cylinder is loaded into a firing furnace. The firing furnace has a temperature profile which brings the cylinder up to 600° C in about 2 hours, and the cylinder soaks for 10 minutes at 600° C. Cooling to room temperature takes about 4 hours.

The cooling rate should not be too short. It is relatively easy to form hairline cracks in the ceramic cylinder due to non-uniform cooling. This does not appear to be as much of a problem during heating.

The cylinder is covered on both bottom and top so that stray silver paint which is blown inside the furnace is not redeposited on the inside wall of the cylinder, nor on the top and the bottom. The procedure for coating the silver must be repeated three times in order to achieve sufficiently high Q's, i.e., spray-dry-fire, spray-dry-fire, spray-dry-fire. If a cylinder is improperly coated, no satisfactory method exists for removing faulty coats other than grinding the finish off using a lathe designed for ceramic grinding. There is a deterioration of the ceramic loss tangent due to the diffusion of the glass frit in the silver paint through the ceramic. Normally, after three fires the glass has not noticeably deteriorated the Q of the cavity; however, after six or seven fires deterioration becomes apparent and Q's of below 5,000 are observed.

Figure 5 shows the silver-coated ceramic cylinder alongside two storage bulbs used in conventional full-size masers. The cylinder is approximately 14 cm O.D., 10 cm I.D., and 15 cm long.

The disks which seal the open ends of the cylinder are similarly fired with three silver coats. Each ceramic disk or endcap is cut to a thickness of 6.35 mm and a diameter equal to the outside diameter of the cylinder. One of the endcaps has a 6 mm hole centered in it for the collimator which determines the relaxation rate of the storage volume. It is only necessary to coat the surface of each of the endcaps which face the cylinder.

At this point, the cavity is tuned to the hydrogen resonance at 1.420 GHz for an oven temperature of 45° C. The tuning of the cavity is accomplished by grinding both the length and inside bore of the ceramic cylinder. Each end of the cylinder is first ground flat to 0.01 mm. This requires usually that about 0.05 to 0.1 mm be taken off each end. Grooves are ground into each end which resemble an O-ring gland with a depth of penetration of 6.35 mm and width of 3 mm. These grooves are used as RF mode suppressors. No RF current flows axially in the desired mode (TE_{011}), but undesired modes do require axial RF currents which are suppressed by this gap due to the groove in the outside electrical boundary at the endcaps. The frequency sensitivity due to changing length of the cylinder is about 400 kHz per mm. The cylinder frequency is now checked using the RF slots located midway between top and bottom of the cylinder and on opposite sides. The TE_{011} mode is readily identifiable by its high Q and cylindrically symmetric field lines. The resonant frequency of the cavity should be about 1.422 GHz at room temperatures for operation in an oven 20° above room temperature, since the cavity frequency coefficient is 100 kHz per degree centigrade. An increase in the temperature causes a decrease in the resonant frequency. The increase in the inside diameter of the cylinder is computed using a cavity frequency coefficient of +4 MHz per 0.1 mm of diameter change. The grinding operation may require several steps in order to come close to 1.422 GHz. If the resonant frequency is cut too high, then the operating oven temperature may be increased to compensate.

With the properly cut cavity with a silver coat and two endcaps each silver coated, the cavity has a symmetric TE_{011} resonance at 1.422 GHz. Symmetry of the resonance over ±10 MHz is better than 3 dB. A spurious mode high in frequency by about 30 MHz is down by 30 dB or more and has very low Q due to the grooves which are cut at the top and bottom ends.

Figure 6 shows a mechanical drawing of the maser and a picture of the complete (sealed) cavity. A copper plate with a slotted, threaded bushing provides a method of fastening a semi-rigid coax line to the cavity sidewall. The end of the coax terminates in an RF coupling loop which penetrates a slot in the ceramic cavity. A nut tightened down on the bushing causes it to compress down to the diameter of the coax. This collet action allows straightforward adjustment of coupling factor. The receiver link is near critical coupling, whereas the exciter link has a coupling coefficient below 0.1.

The cavity is centered lengthwise inside the first magnetic shield using plastic foam at each end of the cavity. An aluminum disc is used at the bottom end for added strength. The C-field is wound on a mylar form located just inside the first magnetic shield, and extends along its entire length (see fig. 7). The windings are one turn per centimeter and are wound from top to bottom to top in a double helix. In this way the tilt of the axis of the C-field due to the coarse pitch of the individual helical windings is subtracted out. Two single turn loops are located at opposing faces of the C-field mylar cylinder for excitation of the Zeeman transition.

There are a total of four magnetic shields concentrically spaced one-half inch apart in a nest. The magnetic shields are fabricated in two halves joined together at the waist with a 5 cm wide overlap joint. The uniformity of the C-field was measured using a rubidium magnetometer. Results showed a homogeneity of at least ± 0.5 nT (± 5 μG) (the resolution of the magnetometer) at an ambient field of 10 nT (100 μG). An axial magnetic shielding coefficient of 1.5×10^5 was measured using these shields. Figure 8 shows the bottom halves of the four nested shields with cavity and C-field coil in place.

A single oven is used to control the temperature of the cavity. Temperature determines a coarse frequency adjustment for the cavity and sensitivity is -100 kHz/°C. The oven is located between the second and third magnetic shields and it is shown in fig. 9. It is an aluminum cylinder with four equally spaced 6Ω titanium heaters running the length of the cylinder. Two precision thermistors with stabilities of about several mK per year are thermally attached to the aluminum cylinder. One thermistor used for the oven controller is located near one of the titanium heaters. The second thermistor, located midway between two heaters, is used as a monitor.

Teflon Coating Technique

The conventional hydrogen maser uses a quartz storage bulb which is coated with teflon. The characteristics of hydrogen wall relaxation depend on the technique of teflon application and the type and purity of teflon.[6] In the small passive maser, no quartz bulb is used and the teflon coat is applied directly to the inside wall of the ceramic dielectric. This is possible because the phase of the axial component of RF magnetic field does not reverse in the hydrogen storage volume, but rather reverses inside the dielectric. The teflon coat serves two purposes. The first is to provide a surface which minimally perturbs the phase of the hydrogen atoms; the second is to vacuum seal the endcaps to the main cylinder.

The teflon coat is made using Dupont FEP 120 emulsion.[5] FEP 120 resins in solution normally contain 50 percent water and about 8 percent triton X-100 stabilizer. The stabilizer tends to (1) keep solid teflon uniformly dispersed, and (2) lower the surface tension by acting as a wetting agent. The liquid emulsion is mixed at 38 percent FEP 120 to 52 percent H_2O to 10 percent triton X-100. This new solution yields a thinner coat, slower initial drying phase, and better wetting of the ceramic surface than the original solution.

The liquid teflon is applied to the ceramic endcaps with a polypropelene squeeze bottle. The surface is uniformly wetted and allowed to dry under a heat lamp for about fifteen minutes. The endcap is placed in a kiln with a heat rise of about 6 K per minute. Pure oxygen is flowed through the kiln during the heating cycles. FEP 120 is fused by melting at a temperature of 360° C. Aluminum foil is placed around the endcap to deflect direct radiant heat from the kiln's heating elements. The rate of heating as one approaches 360° C is important because the high thermal mass of the ceramic causes the ceramic endcap to lag the temperature of the kiln. Thus, fusing of the teflon first takes place at the outside surface of the teflon, trapping stabilizers and other impurities within the teflon. In order to avoid this the rate of temperature increase should be reduced to approximately 1K/min. Three coats of teflon are applied to the ceramic. This lowers the probability that microscopic cracks will increase the effective surface area and that ceramic may be exposed at the bottom of such cracks. Subsequent coats of teflon are applied by using the previous mix and allowing the solution to dry to a very thin overlayer. Milky lumps of teflon may tend to form but this is of no consequence. After an initial dry, the teflon solution is reapplied, wetting is more pronounced, and the lumps dissolve. The surface then dries as before in a uniform thin film, and the same kiln temperature cycle is used After the first coat the surface has a matte finish. By the third coat the surface is glazed and clear.

The application of the teflon mix on the cylinder wall is very similar. It is useful to mount the cylinder in a lathe so that it can be rotated slowly while the liquid solution rolls on the inside wall. The wall is first uniformly wetted, then removed from the lathe and allowed to stand so that the liquid can drip to one end and the solution allowed to dry. Glass endcaps fitted with tubes which go out of the kiln are placed on the top and bottom of the cylinder during the oven cycle so that oxygen can be flowed through the inside bore of the cylinder. Here the oxygen serves two purposes: (1) to oxidize the stabilizer, and (2) to keep the outside surface of the teflon cool relative to the temperature of the heating ceramic cylinder. This is done to insure that fusing first begins at the teflon-ceramic boundary. A thermocouple is mounted in one of the RF slots of the cavity to monitor the temperature profile. Three coats of teflon are applied to the inside wall of the cylinder. Teflon coats can be removed by increasing the oven temperature to about 650° C.

Small Hydrogen Maser Source

The source for the small hydrogen maser is a conventional design. A tank of hydrogen loaded to about 20 atmospheres pressure is fitted with a regulator and mechanical PZT leak valve. From the PZT valve, hydrogen enters the dissociator bulb. A manometer pressure transducer (capacitance type) measures the pressure difference between the hydrogen inlet to the dissociator bulb and the rest of the maser vacuum system, i.e., that portion of the system on the outside of the collimator of the bulb. The discharge bulb is typically 40 μ bar (3 x 10^{-2} Torr). An electronic servo system controls the flow of hydrogen by comparing the output of the manometer gauge with a preset value and providing a correction voltage to be applied to the PZT valve.

In the preparation of the 5 cm O.D., 6 cm long, cylindrical dissociator bulb, no etching solution such as chromic acid is used. The bulb is formed with a fire-polish finish on the inside surface. The collimator has bore dimensions of .304 cm length x .030 cm diameter. After fabrication of the bulb, it is epoxied in a hole in a stainless steel conflat baseplate located at the bottom of the hydrogen maser vacuum system. This is shown in the mechanical drawing of fig. 10. The glass-to-epoxy-to-stainless interconnection is made at a point on the stainless plate where a thin membrane has been cut to yield to differing expansion coefficients.

A cylindrical aluminum cover bolts onto the stainless conflat and protects the dissociator bulb. The cover carries the dissociator electronics. The RF source used in the discharge is a 155 MHz crystal controlled oscillator followed by two buffer amplifiers and a 30 watt LSI power module made by TRW.[5] The RF source electronics draws no more than 15 watts of power; about 8 watts is delivered to the discharge. Measurements indicate that one source bottle of H_2 should last more than four years under normal operating conditions.

Small Hydrogen Maser Vacuum System

The stainless steel vacuum flange carrying the hydrogen source is bolted to the underside of a tubular vacuum system of a total length of 25 cm. The state selector hexapole magnet is supported by the flange. Two 20 l/s vac-ion pumps flank the hexapole state selector and are used to pump away the off-axis beam atoms. A separate 20 l/s vac-ion pump evacuates the top portion. Its function is to pump away the scattered unfocused states in the beam as well as to pump those atoms which have escaped from the cavity. Pump lifetime is estimated at 10 years. A diaphragm separates the source region from the cavity region. A small tubulation in the center of the diaphragm maintains a 20 to 1 pressure difference between these two regions. This tubulation does not affect the beam.

Note that no vacuum system is used on the outside of the cavity. Barometric changes cause only a kHz or so change in cavity tuning which is fully compensated and corrected by the cavity servo system.

Figure 11 shows a picture of the so-called "physics package" of the small maser. The receiver front end and first conversion through a doubly-balanced mixer to an IF frequency of 20 MHz can be seen underneath the outside magnetic shield. Contained here also is the cavity tuning scheme described in ref. 1 and shown in the block diagram of fig. 2.

Frequency Stability Data

Figure 12 shows the two-sample $\sigma_y(\tau)$ data for the first small maser versus NBS-6, one of our primary cesium standards. The length of the data set allowed a determination of frequency stability out to one day of 6.6 x 10^{-12} $\tau^{-1/2}$. Also shown is a frequency stability of 2 x 10^{-12} $\tau^{-1/2}$ of the full-size passive maser using similar electronics. Currently under test is a second small maser which exhibits improved cavity vacuum performance and a better teflon wall coating. The first small maser yielded a hydrogen linewidth of 4.5 Hz. The second maser yields a 1.6 Hz linewidth. From linewidth and signal-to-noise considerations a factor of approximately 5 improvement in frequency stability is expected.

The frequency change of the small maser for a 2 dB increase in excitation power was 2 ± 2 x 10^{-13} while doubling the hydrogen source pressure resulted in a frequency shift of 2 ± 4 x 10^{-13}.

Fractional frequency stabilities of 10^{-15} for long periods of time ($\tau > 100{,}000$ s) appear possible.

Conclusion

We have described the details of a small, passive hydrogen maser using a dielectrically loaded microwave cavity with integral storage bulb and vacuum container. Frequency stability of $6.6 \times 10^{-12} \tau^{-\frac{1}{2}}$ has been observed using this first device. The linewidth of a new small maser has been improved by a factor of 3 to 1.6 Hz. Based on the linewidth and signal-to-noise we expect a factor of approximately 5 improvement in frequency stability.

Acknowledgments

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4. Daniel Kleppner, H. Mark Goldenberg, and Norman F. Ramsey, "Properties of the Hydrogen Maser," Applied Optics, Vol. 1, no. 1, 55, 1962.

5. Commercial equipment is identified in this paper in order to specify adequately the experimental procedure. This identification does not imply recommendation or endorsement by NBS, nor does it imply that the equipment is the best available for the purpose.

6. Jacques Vanier and Robert Larouche, "A comparison of the Wall Shift of TFE and FEP Teflon Coating in the Hydrogen Maser," Metrologia, 14, 31, 1978.

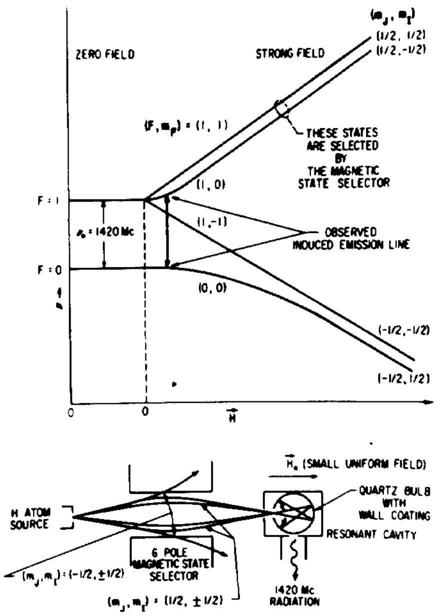
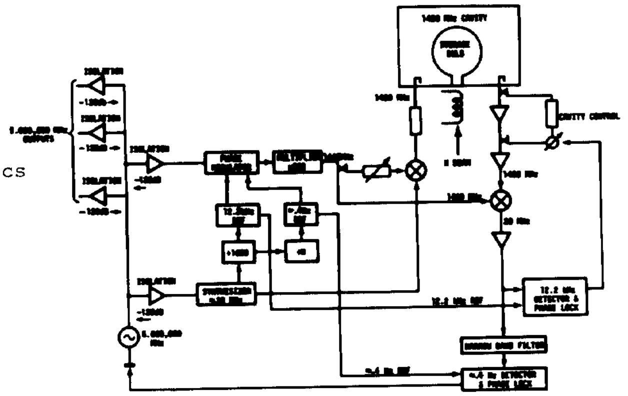


Fig. 1. Magnetic hyperfine transition of hydrogen atom, and maser schematic.

Fig. 2. Block diagram of passive maser electronics



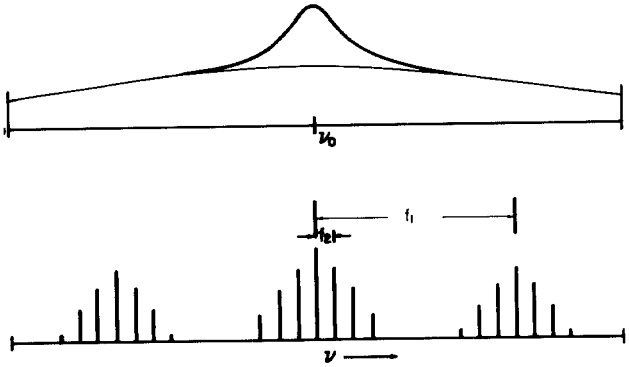
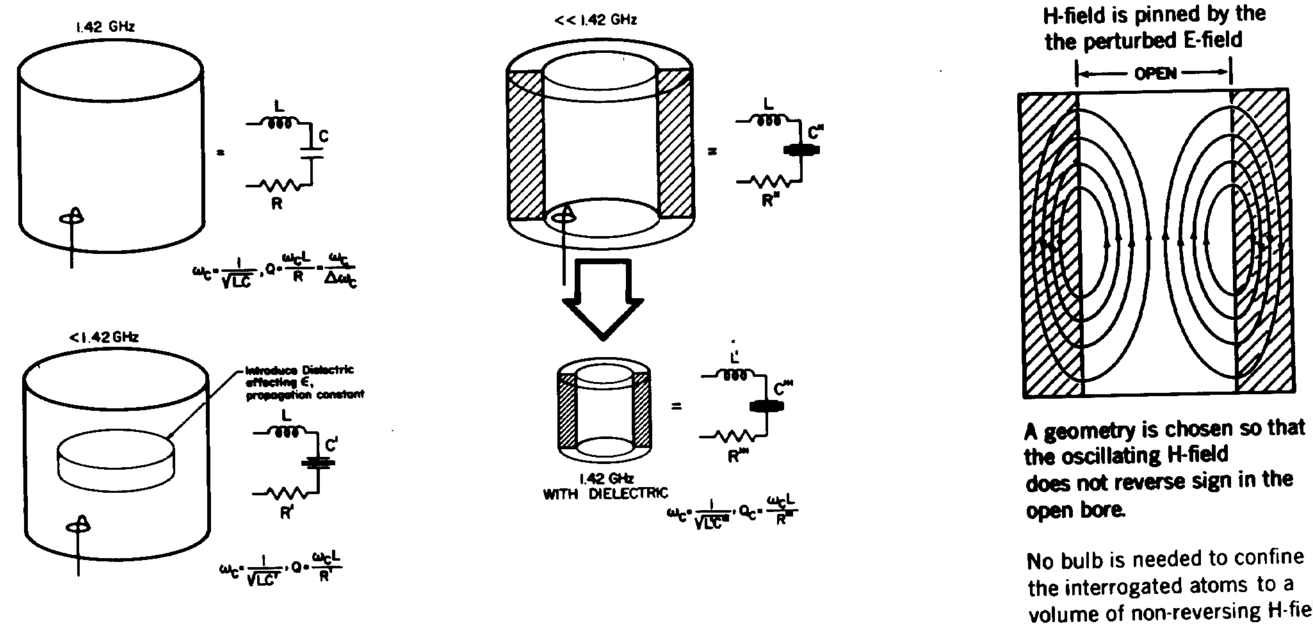


Fig. 3. FM spectrum of exciter signal



H-field is pinned by the the perturbed E-field

A geometry is chosen so that the oscillating H-field does not reverse sign in the open bore.

No bulb is needed to confine the interrogated atoms to a volume of non-reversing H-field

Fig. 4. Dielectric loading of TE_{011} mode cavity allows a reduction in size.

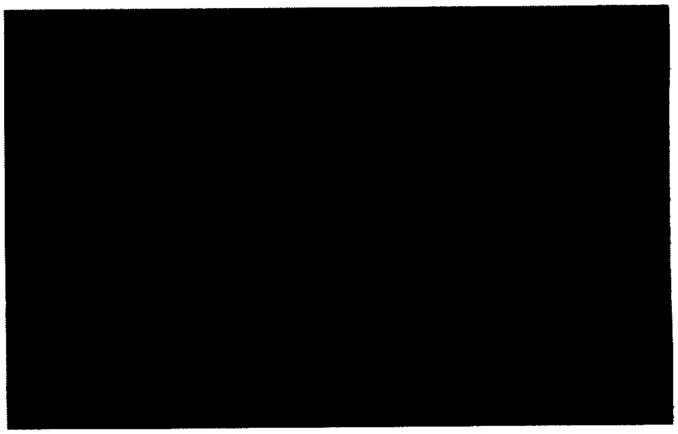


Fig. 5. Size comparison of the dielectrically loaded cavity with storage bulbs of typical full size masers.

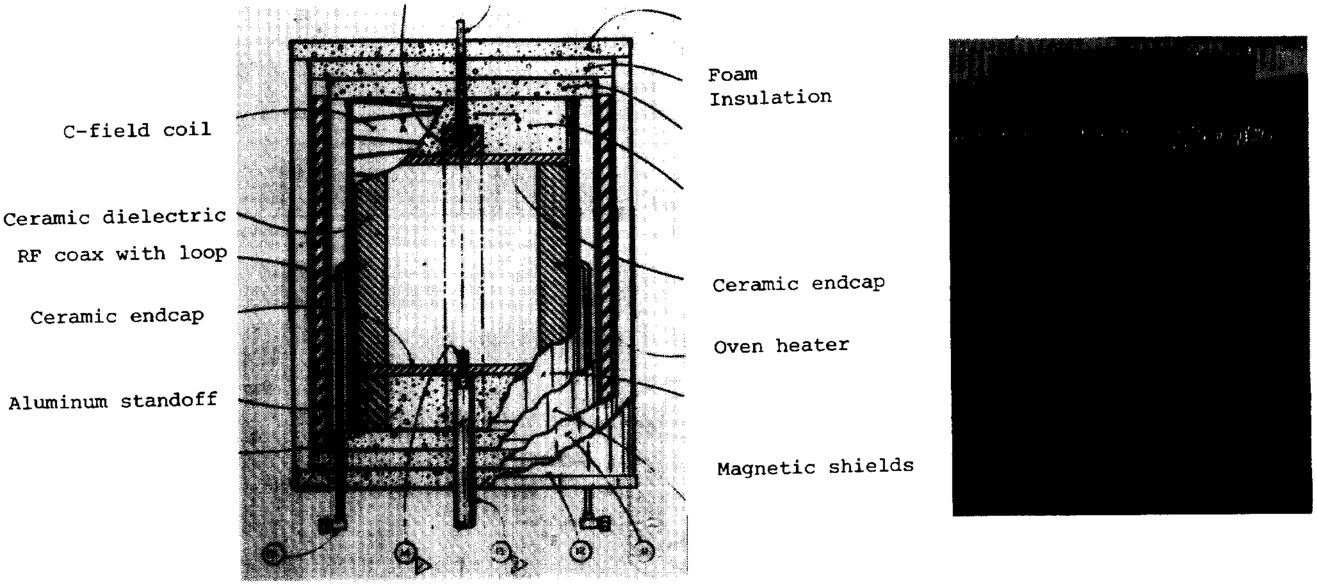
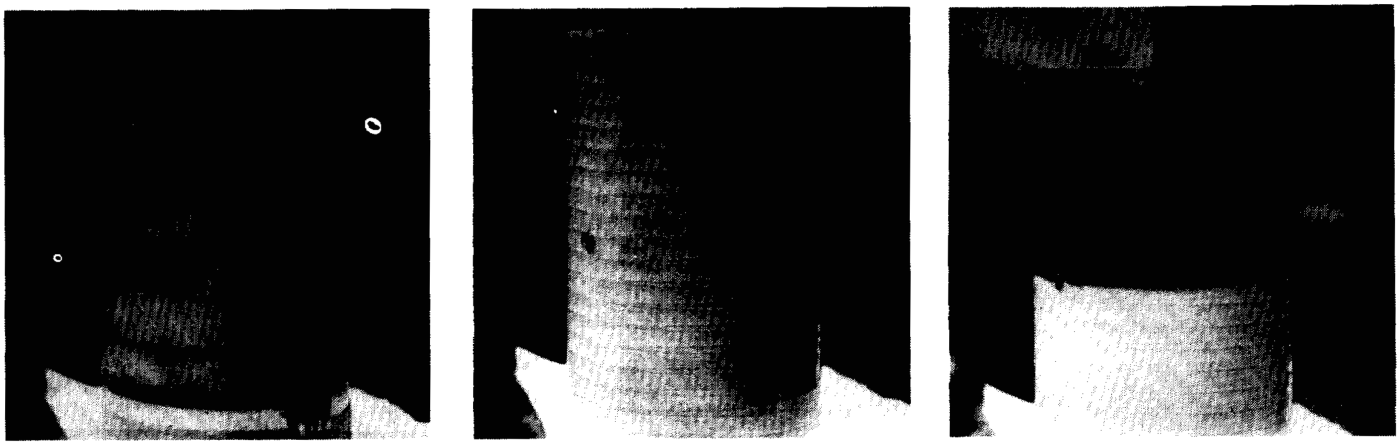


Fig. 6.
Portion of a mechanical drawing showing cavity and shield assembly and picture of cavity collet which accepts semi-rigid coax loop.



(A). Aluminum standoff (top) and degauss strap.

(B). C-field coil.

(C). Bottom of first magnetic shield.

Fig. 7.
Assembly of maser parts inside first magnetic shield.

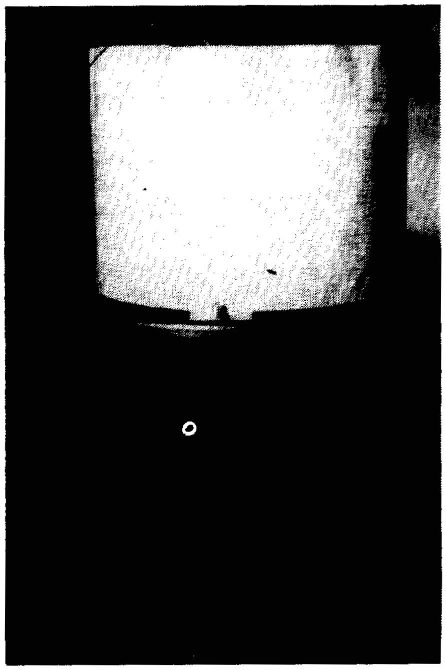


Fig. 8. Picture showing nested shields and sidewall coax RF coupling.

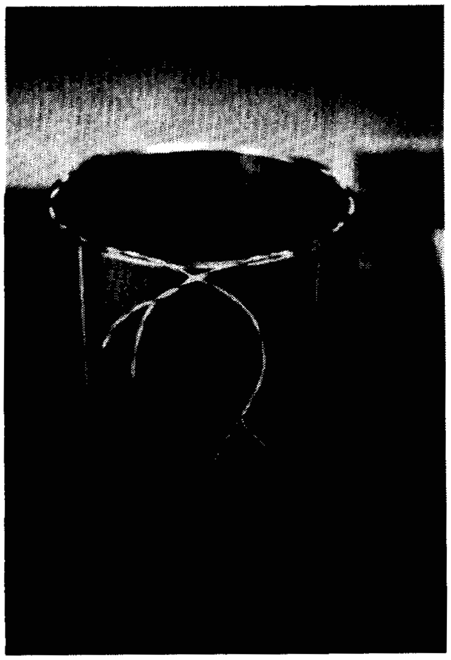
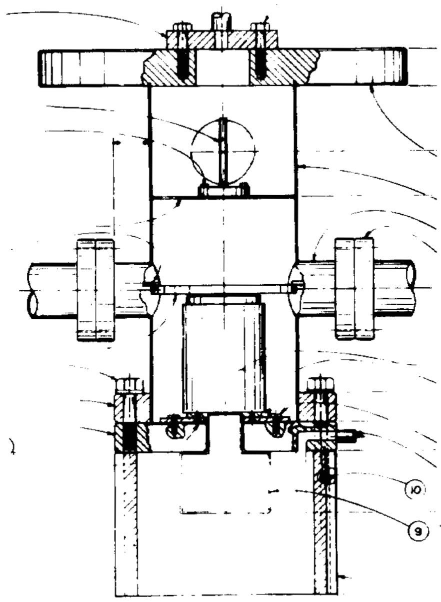


Fig. 9. Oven heater which fits between second and third magnetic shields.



Hexapole state selector

Hydrogen discharge bulb

Cover with attached
discharge electronics
(155 MHz crystal osc.
and power amplifier)

Fig. 10. Mechanical details of source and vacuum system.

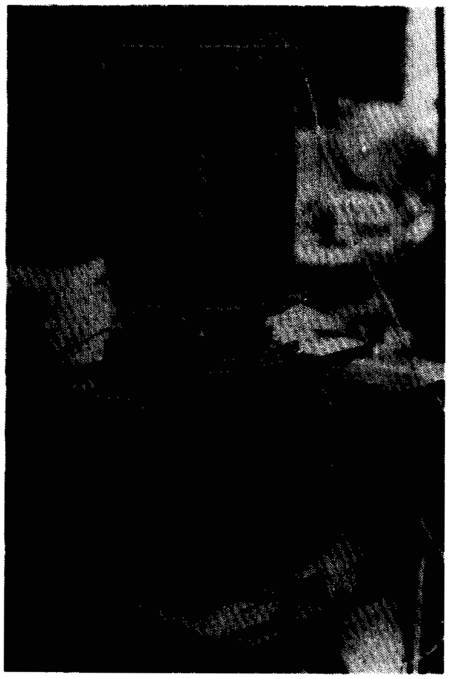


Fig. 11. Complete maser "physics package".

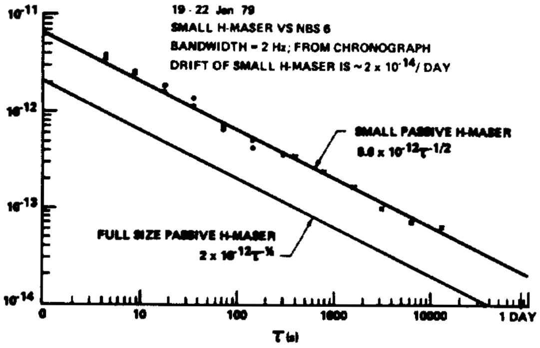


Fig. 12.
Frequency stability of small and full size passive masers.