(12) B.S.

(12) 31p.

(6)

# FEASIBILITY OF SPECIAL PURPOSE ATOMIC STANDARD,

(11) 1977

(10) David J. Wineland

Sponsored by:

Advanced Research Project Agency

(15) ARPA Order 3140

240750

# MIDTERM REPORT

ARPA Order no.: 3140

Program Code no.: 6G10

Name of Contractor: National Bureau of Standards, Boulder, Colorado
In-House

Effective date of Contract: December 15, 1975

Contract expiration date: April 30, 1977

Amount of Contract: $100 K

Contract no.: NBS Cost Center 2774441

Program element code: 62702E

| | |
|---|---|
| Principle investigator: | David J. Wineland<br>(303) 499-1000, ext. 3224 |
| Project scientists: | Helmut Hellwig<br>(303) 499-1000, ext. 3277 |
| | David A. Howe<br>(303) 499-1000, ext. 3209 |
| | David J. Wineland<br>(303) 499-1000, ext. 3224 |

## TITLE: FEASIBILITY OF SPECIAL PURPOSE ATOMIC STANDARD

**The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the Advanced Research Projects Agency or the U.S. Government.**

Letter on file

A

240 750

mt

# TABLE OF CONTENTS

# SUMMARY*

## Technical Problem

The Special Purpose Atomic Standard Project has grown out of a need for a frequency standard satisfying specific requirements not found in other precision oscillators. Briefly, these currently available oscillators can be divided into two classes: the quartz crystal oscillators and atomic "clock" oscillators. The quartz crystal oscillators, while having good short-term stability and low cost ($0.5 to $2 K for high quality units) suffer three major drawbacks: (1) The frequency is not fundamental and is related only to the macroscopic dimensions of the quartz crystal. Therefore calibration is required initially and subsequent recalibration is required due to "aging" of the crystal. Aging rates of 1 part in $10^8$ (fractional frequency change) per year are considered good. (2) The crystal oscillator is sensitive to vibration and shock. These environmental factors affect the macroscopic dimensions of the crystal and therefore can cause step shifts in frequency. (3) The quartz crystal oscillator is temperature sensitive and requires significant warm-up time.

Atomic oscillators provide stabilities from one part in $10^{10}$ to one part in $10^{13}$ per year. Their cost ranges from $3,000 to above $20,000 depending upon performance. Their high frequency stability and accuracy make recalibration unnecessary for most applications. It must be realized that the use of presently available atomic oscillators in place of crystal oscillators for the purpose of avoiding recalibration routines or reducing environmental sensitivity is technical "overkill" since the excellent performance of today's atomic oscillators (obtained at high cost) is not really required for most applications. In addition, their warm-up time is slow and their performance under severe environmental conditions (acceleration, vibration, temperature, barometric pressure and magnetic fields) is inadequate

---

*This report is identical to that prepared as a final report for work sponsored by ADTC/XRO, Eglin AFB, MIPR #FY7620-76-90128, Attn: Ralph L. Brown, Lt. Col., USAF, Chief, Weapons Division.

for some applications.

Therefore a special purpose oscillator or clock with frequency accuracy in the $10^{-9}$ range and frequency stability in the $10^{-10}$ to $10^{-11}$ range would satisfy the needs of many technical applications if low cost and insensitivity to environment could be obtained. Fig. 1 shows the frequency stability desired (solid line).

## General Methodology

In order to meet the above requirements we might hope to look for a system which incorporates the desirable features of both the atomic oscillators (high accuracy, stability) and crystal oscillators (low cost) and includes features of environmental insensitivity and possibly fast warm-up. Since we are not after ultimate accuracy and stability we might make sacrifices in this regard. After careful consideration we decided to investigate the possibility of using an oscillator which is referenced to an absorption line (for accuracy) in a molecular (or atomic) gas. This is, of course, the same principle of operation as the cesium, rubidium or hydrogen standard. However, since we are willing to sacrifice some stability and accuracy we simplify the hardware significantly by containing the reference molecule (atom) in a simple closed cell. We have chosen as frequency reference the (3-3) transition in ammonia ($NH_3$) gas ($\sim$24 GHz). Historically [1] this same scheme was used in the first "atomic" clock in 1948. Research on this basic device was persued until about 1955 but was dropped then because new methods, although more complicated, promised better accuracies and stabilities than a gas cell absorption device. In 1955, the accuracy of an ammonia device [2] was only about 5 parts in $10^8$ with approximately 1 part in $10^8$ stability and the apparatus was quite complicated and expensive, suitable only as a laboratory instrument. However since that time, vast improvements have been made in RF and microwave electronics; this coupled with new insights into the electronic and physical problems encountered led us to conclude that the ammonia absorption cell idea could be used to provide the "special purpose" oscillator described above.

The basic scheme used for the standard is shown in Fig. 2. For simplicity and economy, the primary oscillator in the system is at ∿500 MHz. With this, one can multiply in one step to ∿24 GHz with ample output power to drive the ammonia transition. In addition one can directly divide the 500 MHz signal to produce a convenient output between 5 and 10 MHz.

## Technical Results

The basic features of the system shown in Fig. 2 have been realized. For convenience we have broken the problem into four main areas. (1) 0.5 GHz primary oscillator and divider, (2) 0.5 GHz to 24 GHz multiplier, (3) ammonia gas cell and (4) servo electronics.

(1) In reviewing the possible oscillator designs it was evident that an oscillator using a P.C. board etched strip as the resonator was feasible. Such a stripline oscillator has been developed with good short-term stability in mind. The free running frequency stability is shown in Fig. 1. The oscillator has a fundamental frequency of 0.5 GHz and features a wide tuning range of about 100 MHz. Short-term stability is ample for use as the primary oscillator.

The curves of Fig. 1 for the oscillator also include a divider chain after the 0.5 GHz oscillator. The output frequency is nominally 5 MHz for lab and systems use. The chosen frequency for the stripline oscillator was fundamentally governed by the high frequency limit for currently available low-cost dividers.

(2) The 0.5 GHz to 24 GHz multiplier was a crucial element in the project because of the commercial unavailability of any K band (18 - 26 GHz) source with high enough spectral purity and power to accomplish the goals of the project. It was also important to build such a source as early as possible in order to investigate the details of gas cell and servo electronics design. The required multiplier was also not readily available commercially; therefore we have designed and built a module to multiply from 518.9 MHz to

23.87 GHz in one step using a step-recovery diode. We have achieved a stable, "broad" band (Q = ∿10) device with ∿100 μw output (5 times more power than needed). This has been integrated with a hybrid microstrip amplifier (500 MHz) to provide this output power with a few milliwatts input power.

(3) The ammonia gas cell was built with simplicity in mind. For test purposes we have used sections of X and K band wave guide filled with ammonia using a variable pressure, gas flow vacuum pumping station. We have also built compact cells using metal plated glass tubes which are formed into spirals (less than 10" dia.) to increase effective cell length without increasing overall size. Such cells are also important to reduce temperature-pressure effects because ammonia tends to stick to the walls of the gas cell. These problems are reduced in an ulta clean glass cell with suitable non-sticky walls (e.g. teflon coating).

(4) The servo electronics must necessarily be fairly sophisticated because we are locking the primary oscillator to a broad resonance and requiring that the servo electronics discriminate to better than 0.001% of this resonance feature. Three primary sources of distortion (and therefore reduced accuracy and stability) are: (1) frequency pulling due to frequency dependence in the source output power and detected power, (2) frequency pulling due to the resonance "cavity" seen by the ammonia, (3) frequency offsets due to offset voltages and distortions in the servo electronics. These problems have been largely eliminated by using frequency modulation (∿10 KHz) on the 0.5 GHz oscillator, locking the oscillator to the center of the ammonia resonance using the 3rd harmonic of the detected FM and, in turn, locking the cavity to the oscillator using the 5th harmonic of the detected FM.

The frequency stability [3] data achieved so far using the integrated system is shown in Fig. 1. This shows that we have satisfied the desired stability out to between 10 and 100 seconds and hence the long-term stability must now be improved. It should be noted that the problems of 0.5 GHz oscillator, divider, multiplier and servo electronics have been largely solved at this time and much progress has been made in the cell development. Such an approach was natural in the sense that the short-term stability must necessarily be good before the long-term stability problem can be addressed.

## Implication for Further Research

The main remaining problem is to find a gas cell configuration which reduces temperature sensitivity, (i.e. pressure shift and warm-up problem) and efforts have already been started in this direction. This along with some remaining servo problems appear to be the main limitations in achieving good long-term stability and accuracy. Vibration and shock analysis must be experimentally investigated, and we are optimistic since the ammonia resonance itself is vibration insensitive to an extremely high degree; this coupled with the available short attack times of the servo loop greatly reduces the influence on the primary oscillator.

Based on our present results, for a future unit we estimate an approximate size of 2000 cc, weight 2 kg and 3 W power consumption.

## I. General Features of system

### 1. Introduction

It might of course be desirable to use an existing atomic oscillator (rubidium, hydrogen, cesium) to accomplish the goals of the special purpose frequency standard. However, the increased complexity and sophistication of these devices which results in their superior performance are just the factors which increase their cost and decrease their reliability in an adverse environment. This sophistication is introduced primarily to make the reference transition free from first-order Doppler broadening to a high degree. This results increased line Q and therefore increased accuracy and stability. In the approach chosen here we contain the reference "atom", the ammonia molecule, in a closed waveguide cell and therefore the linewidth is limited by Doppler broadening to give a fundamental upper limit on line $Q \simeq 3 \times 10^5$. This can be compared to the line Q's of the high performance atomic oscillators [4]:

$$Q(Rb) \simeq 3 \times 10^7 \qquad Q(H) \simeq 10^9 \qquad Q(Cs) \simeq 3 \times 10^7.$$

Therefore, sacrificing resolution, we obtain a much simpler system resulting in a significantly reduced cost and increased reliability. Also, the lower line Q allows fast servo loops within the standard, thus reducing the effects of adverse environments.

The basic scheme we have chosen was investigated in the early 1950's but was dropped when Doppler linewidth narrowing techniques became practical. Since that time significant improvements in electronics have made the problems of microwave power generation and electronics simpler, and we therefore can expect to construct a fairly rugged simple system around the basic ammonia absorption cell. A more detailed diagram of the present system is shown in Fig. 3.

### 2. Microwave Source

In specifying a possible fundamental oscillator for the standard, one has reasons for not using a microwave oscillator. They are: (1) Even a high quality YIG-tuned Gunn oscillator draws too much power (40 W), is too expensive (∿ $2500), and is not stable enough (by a factor of at least 10) in short-term to be useful as a primary oscillator. (2) In order to compare an output frequency of between 5 and 10 MHz to the ammonia transition frequency we require a multiplier chain to compare to the microwave primary oscillator. (Note that few dividers exceed ∿ 1 GHz input frequency, therefore we could not divide directly from ∿ 24 GHz.) The development of a special 500 MHz oscillator is more practical as shown in the diagram of Fig. 2.

### 3. Gas Cell

The advantages of using the ammonia gas cell as a reference are:

(1) The RF transition of interest provides a signal which is orders of magnitude stronger than those of other interesting molecules or atoms [5]. This is a significant advantage because it means that the desired signal-to-noise is obtained without resorting to impractically large microwave cell sizes as would be necessary for almost any other gas.

(2) Since ammonia remains in gas phase for the temperature range of interest ($-40^{o}$ C to $+60^{o}$ C) the device has instant turn-on capability. One must, however, note the existence of a pressure (therefore temperature) dependent frequency shift; this is discussed more fully in Section II.4(a).

(3) The ammonia transition is, of course, fundamental in nature and therefore essentially eliminates the need for calibration of the device.

(4) The ammonia transition linewidth is fairly broad (∿ 100 kHz). This is a disadvantage in terms of the ultimate accuracy obtainable, but it allows the primary oscillator to be locked to the ammonia reference in very short times (< 1 ms). The advantage here is that the vibration sensitivity of the primary 500 MHz oscillator is reduced by as much as the open loop gain of the servo system at the vibration frequency of interest.

### 4. Integrated system

The entire system shown in Fig. 3 has been realized. For ease of testing, the prototype 500 MHz oscillator has not been fully integrated into the system yet. For testing the multiplier, gas cell and servo electronics we have used a commercial oscillator (HP 8640 B). The full integration is not expected to be a problem since the new stripline oscillator is already more stable in short-term (< 0.1 sec) than the commercial oscillator.

## II. TECHNICAL RESULTS

### 1. Introduction

For ease of discussion and clarity, it is convenient to divide the system into four main areas:

(1) ∿ 500 MHz primary oscillator and divider,
(2) ∿ 500 MHz to ∿24 GHz multiplier,
(3) ammonia gas cell,
(4) servo electronics and integrated system.

Each of these areas is discussed below along with results.

### 2. 500 MHz primary oscillator and divider

In reviewing the possible oscillator designs, it appeared that an oscillator using a simple LC resonator should be investigated. Advantages to this design include:

(1) wide tunability
(2) more likelihood for survival under very adverse conditions (shock, vibration),
(3) good short-term stability,
(4) low cost.

The rationale for research toward designing an adequate LC oscillator is two-fold: (1) vibration sensitivity would be effectively dealt with since the oscillator could frequency lock to the $NH_3$ absorption line in short-term, (2) greater flexibility exists in the total system design because the choice of oscillator frequencies covers a wider range than is afforded by quartz crystals. With regard to Item 2, it is possible to reconfigure the frequency standard to obtain a variety of output frequencies with relative ease thus facilitating frequency synthesis for some applications.

It is desirable to operate the primary oscillator at a high frequency to reduce the multiplication factor needed to generate the microwave signal. At the same time, one needs to derive a usable, convenient low frequency (nominally 5 MHz) for lab and systems use. A digital divider is a simple and reliable solution to obtaining lower output frequencies. The upper frequency limit for such devices is currently 0.5 to 1 GHz in the case of low-cost dividers.

An oscillator was developed operating at about 0.5 GHz and having a free-running stability as shown in Fig. 1. These data were computed using the two-sample variance for different averaging times [3]. The bandwidth of the measurement system affects the variance in the case of white and flicker of phase type noise, so two curves are plotted around the averaging times of interest (∿ 10 ms). The oscillator features a P.C. board etched strip as a transmission line resonator (stripline resonator). In the design of a high-performance stripline oscillator, one must address three principle problems [6]:

(1) minimization of resonator losses,
(2) minimization of additive transistor noise, and
(3) shock and vibration isolation of the resonator.

There are other problems which must be looked at, but these three represent the major contributors to degradation in stability.

One seeks maximum Q (quality factor) from the transmission line resonator in order to filter out wideband white phase noise generated in the oscillator. Resonator losses occur due to radiative loss, real-part loss (resistive and dielectric), and loading due to attached circuitry [7].

Radiative loss is minimized by adopting a three-layer, sandwich etch technique. In this design, two ground planes are used on the top and bottom surfaces of the P.C. board with the stripline centered in the dielectric. Fig. 4 shows a cross-section of the line. Fiberglass-teflon is used for the dielectric which has a low loss tangent of about $10^{-3}$, thus keeping the real-part loss at a minimum. The stripline itself is a 7 cm length of copper which is 1 cm wide and 2 mm thick which yields a low resistive loss. Contact resistance is minimized by using silver-solder on all connections. The unloaded Q of the line resonator at 0.5 GHz is about 400. Loaded Q of the resonator is maximized by the use of a field-effect transistor as the active element [8]. It is chosen to have a high forward transconductance and a high cut-off frequency.

Also considered in the choice of the transistor is manufacturing tolerance and package and device inductance and capacitance. In a volume production situation where oscillators must work within some range of frequencies after fabrication, package and device parameters need to be uniform from unit to unit.

Additive transistor noise in this configuration is due primarily to low frequency (near carrier) flicker noise behavior and high frequency (far from carrier) white phase noise. Flicker behavior is difficult to deal with in many instances. Helpful in the reduction of flicker noise is a transistor which is manufactured with care and in a clean environment, since flicker noise may relate to sporadic conductance through the device due to impurities. White phase noise is usually associated with thermal noise and the noise floor imposed due to operation of the device at room temperatures. One can then resort to devices capable of higher current densities in order to get considerably above the noise floor. A trade-off exists between white phase and flicker noise, however, since higher device currents usually aggrevate the flicker noise problem. Most times, one arrives at a compromise solution which depends directly on the application of the oscillator. The curves shown in Fig. 1 represent a much higher device drive level than is common in, say, quartz crystal oscillators.

The transistor used in our tests was the U310 manufactured by Siliconix Incorporated. It generally conformed to all of the requirements of the necessary device. In the case of high volume production of the oscillator, one may be well-advised to fabricate a transistor especially for this application.

At frequencies around 0.5 GHz, transistor package parameters (inductance and capacitance) and stray parasitic elements such as connecting lead inductance and stray capacitance all contribute to the fundamental resonance. If one is to achieve frequency stability approaching 1 x $10^{-9}$, then it is imperative to maintain resonator inductance and capacitance fixed to this level. The greatest deterrant to maintaining high inductive and capacitive stability is vibration sensitivity of the oscillator. This problem of microphonics has been reduced by using the three-layer P.C. board and rigidly mounting all components and leads with a low-loss doping compound. The oscillator is in turn rigidly fixed to an aluminum block which acts as the shield for the components. The block weighs about 3 kg. Depending on the application, one can rigidly mount or soft mount the oscillator into a system. If rigidly mounted, structure-born vibration is directly applied to the oscillator. A soft mount designed to isolate the oscillator from vibration can reduce the transmitted vibration at higher frequencies at the cost of a resonance increasing the vibration at a lower frequency. Damping material can also be used to alter the vibration response.

In the ammonia standard, the problem of vibration sensitivity of the fundamental oscillator is only significant in extreme cases of shock and vibration where the dynamic range of the servo system is exceeded or the period of the vibration is shorter than the servo attack time. The servo attack time can be smaller than 100 μs since the $NH_3$ resonance is wider than 10 kHz. Thus, the design of the oscillator mount should yield a vibration response in which frequencies of 10 kHz and above are suitably attenuated.

The curves in Fig. 1 for the oscillator also include a divider chain after the 500 MHz oscillator. Presently the short-term noise is predominantly noise from the divider. The output frequency is nominally 5 MHz for lab and systems use. The chosen frequency for the stripline oscillator is ultimately governed by the high frequency limit for currently available, low cost dividers.

### 3. Step recovery diode multiplier

It was important to build such a multiplier as early as possible in the project because a Klystron and YIG-tuned Gunn diode oscillator could not yield good data on the short-term stability of the system. Also these oscillators had fairly high Q's in the output circuits which tended to pull the oscillation due to line distortion. [See Section II.5(a)]. Since existing ∿ 500 MHz oscillators (we used HP 8640 B) had good enough short-term stability, it was therefore desirable to make a multiplier module with fairly low output Q ($Q \simeq 10$) and output power ∿ 100 μW. A rather large body of work has been done at lower frequencies (< 18 GHz output) [9] but very little work has been done above 18 GHz. After soliciting a large number of companies, we did receive a quote from a microwave systems company for construction of such a device but cost was somewhat high ($20,000) and more importantly delivery was several months. Therefore, it became necessary for us to design a module to accomplish the specific goals of the project.

We have used state-of-the-art step-recovery diodes in a waveguide multiplier module which is shown in Fig. 5. In simplest terms, the problem is one of impedance matching for both the input and output frequencies. For example, for the input circuit (∿ 500 MHz) the dynamic diode impedance is $|Z| \sim 1\Omega$. Therefore, two $\pi$ section transformers were cascaded to match to the $50\Omega$ output impedance of the amplifier. Approximately 0.5 to 0.75 W input power is needed to "snap" the diode properly. To accomplish this, a microstrip hybrid class "C" amplifier was used. The amplifier, microstrip matching circuit and multiplier module were integrated into one package in order to avoid instabilities due to connections. The output circuit was composed of shorting stub and iris coupling to form a cavity $Q \simeq 10$ with the diode matched to the characteristic impedance of the narrow height waveguide. A taper was then used to match to standard K band hardware. In the interest of rigidity and simplicity, shims were used rather than movable plungers. With $\sim$ 0.6 W input power to the diode, output power as shown in Fig. 6 was obtained. This power is about 5 times what is needed in the system. The parameters of the multiplier module are nearly optimized, and we have demonstrated the feasibility of the use of such a multiplier module in the overall system.

## 4. Ammonia gas cell

The ammonia gas cell is fairly straight forward in principle but must be refined to compensate for those effects which influence frequency stability and accuracy. For initial experiments, relatively short cells (50 cm - 100 cm long) were constructed of K or X band waveguide stock. In order to study pressure related effects (i.e. broadening and shifts), a flow system was constructed as shown in Fig. 7. The waveguide cells are sealed using mica windows and indium seals.

### 4a. Pressure problems

It should be noted that standard X or K band cells with copper surfaces will not be suitable for final permanently sealed cells because copper is harder to clean than other vacuum materials. Also, ammonia sticks to most surfaces (including copper) because of its relatively large electric polarizaility; this accentuates the pressure shift. The pressure shift problem contributes to the limit of long-term stability and accuracy. If there were no pressure shift, we would like to operate at a pressure as high as possible but not have the line be broadened by pressure broadening. This occurs for $p \simeq 5 \times 10^{-3}$ Torr. We have approximately measured the shift, and it has been previously reported that the fractional frequency shift due to pressure is [10]:

$$\frac{\nu-\nu_o}{\nu_o} \simeq 2 \times 10^{-5} p$$

where p is in mm Hg (Torr). Therefore, if we operated at a pressure of $5 \times 10^{-3}$ Torr, we incur an absolute frequency shift of $10^{-7}$ and, therefore, need to know the pressure to 1% to obtain $10^{-9}$ accuracy. Assuming no sticking of ammonia to the walls, one would have to hold the temperature of the gas to 0.3° C in order to obtain $10^{-10}$ long-term stability.

Three approaches exist to overcome these basic pressure effects: (1) One must first insure that sticking on the walls is kept to a minimum; if not, then the temperature effect is enhanced because the pressure increases more than linearly with temperature. This is because molecules will be released from the surface as well as speeded up by temperature increases. To this end we have started work on using cells with various interior cell surfaces (e.g. glass, Teflon).

(2) Roughly speaking, we can gain in signal-to-noise linearly with the volume of the gas. One can therefore expect to increase the cell size and reduce the pressure (and, therefore, the pressure shift) and still keep the same signal-to-noise. We expect to be able to gain a factor of about 50 from this. Incorporating (1) and (2) from the above, this would reduce the basic temperature sensitivity of the system to $6 \times 10^{-11}/^{\circ}$ C. This is to be compared to the basic (uncompensated) temperature sensitivity of the rubidium atomic clock which is about $1 \times 10^{-10}/^{\circ}$ C.

(3) One can use compensation schemes whereby the pressure is sensed and approximate compensation is made in the output frequency.

Since the projected cell size may be as large as 1000 $cm^3$, one must work on schemes to make it convenient in a compact package. A straightforward way to make the cell larger is to make it longer. We can then make it into a spiral. Some preliminary experiments which are encouraging use glass tubes, which are metal plated on the outside (forming circular cross-section waveguide) which are formed into spirals (∿ 10" diameter) and mated to standard waveguide flanges.

## 5. Servo electronics and integrated system

Although the overall performance of the device is not high when compared to a state-of-the-art atomic clock, the demands on the servo system in the final system are rather high. This is because we are trying to resolve the rather broad resonance feature (i.e. "split the line") to about $10^{-5}$ or 0.001%. This is within an order of magnitude of the servo requirements on a laboratory cesium standard. This means one must be particularly careful about harmonic distortion in the modulation and D.C. offsets in the feedback integrators. The most important problems which we face are: (a) frequency pulling due to frequency dependence in the source output power and detected power (source-detector profile), (b) frequency pulling due to the resonance cavity seen by the ammonia (cavity pulling), (c) frequency pulling due to fundamental line distortion, and (d) frequency pulling due to offset voltages and distortions in the servo electronics (servo offsets).

### 5(a). Source-detector profile

The source power output and detector efficiency are in general frequency dependent; thus the observed transition rides on top of a broad profile. Because this background may have a slope and curvature at the transition frequency, it distorts the line slightly and causes a frequency shift. Since this background profile may change in time (due for example to temperature change) it affects both long-term stability as well as accuracy. To solve this problem, we borrow a technique used in stabilized laser work [11]. One can lock to the third harmonic of the FM rather than the fundamental; by doing this, one nulls out the third derivitive of the slope rather than first. This is useful because it lowers the profile pulling by approximately the square of the ratio of the background curvature to the curvature of the resonance line. The effects of such a 3rd harmonic lock are shown in Fig. 1, where a definite improvement in stability is observed (until other effects dominate).

### 5(b). Cavity pulling

This is a familiar problem in all atomic clocks to varying degrees and has been documented elsewhere [12]. Very simply, the ammonia and microwave cavity form a system of coupled oscillators. Therefore varying the frequency of one (say the cavity) changes the frequency of the other (ammonia transition). We have:

$$\nu(\text{observed}) - \nu_o = K \frac{Q_c}{Q_\ell} (\nu_c - \nu_o)$$

where $\nu_o$ = unperturbed ammonia frequency,

$Q_c$ = microwave cavity Q,

$Q_\ell$ = ammonia transition Q,

$\nu_c$ = cavity frequency, and

$K \simeq 1$.

If one tries to terminate the ammonia cell as well as practical (e.g. VSWR ≃ 1.01) and if the cell were 100 half wavelengths long, we have $Q_c = 1$. With $Q_\ell = 2 \times 10^5$, we would have to tune the center of this cavity to 0.02% in order to achieve $10^{-9}$ accuracy; temperature sensitivity would be $\sim 2 \times 10^{-10}/^\circ$ C for a copper cavity. Both of these problems are circumvented by servoing the center of the cavity to line center. This can be accomplished if one realizes that K in the above expression is different if we lock to the 3rd harmonic rather than if we lock to the 5th harmonic (extension of the 3rd harmonic technique). Therefore, as shown in Fig. 3, we use the 3rd harmonic to lock the oscillator to the apparent line center, then use the 5th harmonic to lock the cavity to the oscillator. This insures $(\nu_c - \nu_o) = 0$ in the above expression and therefore eliminates cavity pulling. The results of locking the cavity on long-term stability are illustrated in Fig. 8.

## 5(c). Fundamental line distortion

The $N^{14}H_3$ (3-3) transition is slightly asymmetric due to quadrapole hyperfine structure in the molecule [5]. Therefore the apparent center frequency of the line depends on FM amplitude and microwave power; stability is correspondingly affected as these parameters change. We do not feel this will be a problem; however, if it turns out to be a problem, the simplest solution would be to use the (3-3) transition in $N^{15}H_3$ which is free of these fundamental distortions.

### 5(d). Servo offsets

At the present time, voltage offsets and voltage offset drifts in the servo system along with the pressure shift problem seem to limit long-term stability. For example, an offset voltage can exist on the input of the first integrator in the third harmonic loop (see Fig. 3). With the system locked up, a residual 3rd harmonic signal must be present to provide a D.C. level out of the mixer to compensate this offset. These servo problems are fairly straightforward and we are confident of their elimination.

We note that an FM frequency of $\sim$ 10 kHz is used and double integrators are used to eliminate frequency offsets in the locked system due to a free running oscillator which might have linear drift. The harmonic filter is used to prevent frequency offsets due to FM distortion. The present attack time of the servo is approximately 4 ms.

## III. ENVIRONMENTAL FACTORS

Sensitivity to environmental factors is most easily determined experimentally and this will be quite straight forward once some of the obvious problems limiting long-term stability are solved. Nevertheless, theoretical estimates can be made of magnetic field and electric field sensitivity and other remarks are appropriate for vibration and temperature sensitivity.

### 1. Magnetic fields

First-order Zeeman effects cause a splitting of the line on the order of 1 kHz per oersted. This splitting is symmetric and therefore causes only (usually negligible) broadening except that some asymmetry may be present due to slight differences of the Zeeman effect (uncoupling of the spins) in the two inversion levels. This asymmetry may be of the order of 1 Hz at 1 oersted. Measurements need to be made to quantitatively assess this effect. The worst anticipated outcome is the need for one simple magnetic shield for some applications in very high fields.

The second-order Zeeman effect is, of course, exceedingly small: It is about $2 \times 10^{-15} H^2$ (H in oersted) and thus negligible.

### 2. Electric fields

Electric fields are only of importance in the construction details of the gas cell where thermo-electric and contact potential problems may be present. A worst estimate can be based on the most sensitive hyperfine component of the (3-3) line; for this we have about $10^{-9} E^2$ (E in V/cm). Since electric fields surely can be limited to less tha 0.1 V/cm, we do not anticipate any problems.

### 3. Temperature sensitivity

This has already been discussed in Section II.4(a). For best performance it may be necessary to provide some minimal temperature compensation (i.e. a frequency compensation based on the temperature). At least a factor of ten improvement could be expected here; this would then reduce the overall temperature sensitivity by a factor of ten.

### 4. Vibration sensitivity

It is difficult to predict a priori what the limits to vibration sensitivity should be since in many cases they result from mechanical contruction imperfections which are most easily eliminated by an experimental approach. However, some general comments could be made in this regard. To a high degree the ammonia cell and servo electronics should be vibration insensitive. We can expect then that the vibration sensitivity of the 500 MHz primary oscillator should be reduced by the open loop gain of the feedback servo. Therefore if the attack time of the servo is $\tau = 0.1$ ms, then the vibration sensitivity of the locked oscillator at say 100 Hz should be reduced by a factor of approximately $10^4$ over the free-running oscillator.

The oscillator has of course been designed with mechanical rigidity in mind. We now plan to test the basic oscillator on a shake table; once the oscillator has been made vibration insensitive as much as possible, the whole system can be tested in a similar way.

## IV. OVERALL PHYSICAL PARAMETERS

### 1. Power requirements

The basic electronic components of the present standard configuration are shown in Fig. 2. The power requirements needed for specific portions are at present:

| | | |
|---|---|---|
| (1) | 500 MHz oscillator, 500 MHz buffer amplifier with multiplier | 5.5 W |
| (2) | divider chain ( ÷ 100) | 1.0 W |
| (3) | detector amplifier and servo | 1.0 W |
| | | 7.5 W total |

The 0.5 GHz buffer amplifier is the major drain on the power supply. Since the multiplier step-recovery diode needs about 1 W R.F. output, the efficiency of the amplifier combined with the matching network to the diode is at best about 20%. In an actual system we could expect total power requirements to be approximately half of their present value or $\sim$ 3 W.

### 2. Size requirements

The lower limit on size will primarily be limited by the size of the ammonia cell. It is expected that the cell should occupy no more than 1 liter volume; hence the overall package may be from 1 - 2 liters in volume.

### 3. Weight requirement

With proper choice of materials the expected final package weight should be less than 3 Kg. For operation in extreme magnetic fields, shielding may have to be included, this will increase weight by approximately 1/2 Kg.

## V. CONCLUSIONS

With the contract period about half over, we feel that we have solved a majority of the problems involved in reaching the proposed goals, have already addressed the remaining problems, and are optimistic about their solution. As described in the text, our most difficult remaining problem may be to reach good long-term stability and, therefore, much of our effort is concentrated in this direction. We will now start vibration sensitivity tests and are again quite optimistic in this regard.

# REFERENCES

[1] LYONS, H., Annals New York Acad. Sci., 55, 831 (1952).

[2] SHIMODA, K., "Atomic Clocks and Frequency Standard on Ammonia Line I" and "III",J. Phys. Soc. Japan, 9, June 1954, pp. 378-386 and pp. 567-575.

[3] ALLAN, D.W., "Statistics of Atomic Frequency Standards," Proc. IEEE, 54, February 1966, pp. 221-230.

[4] HELLWIG, H., "A Review of Precision Oscillators," National Bureau of Standards Technical Note 662, February 1975.

[5] TOWNES, C.H., SCHAWLOW, A.L., Microwave Spectroscopy, McGraw-Hill Book Co., New York, 1955.

[6] HODOWANEC, G., "Microwave Transistor Oscillators," RCA Application Note AN 6291.

[7] PRESSER, A., "RF Properties of Microstrip Line," *Microwaves,* March 1968, pp. 53-55.

[8] OXNER, E., "High-performance FETs in Low Noise Oscillators," Siliconix Incorporated, December 1973.

[9] See for example:
"Ku-band Step Recovery Multipliers," Hewlett-Packard Application Note 928.
Also:
"Harmonic Generation Using Step Recovery Diodes and SRD Modules," Hewlett-Packard Applications Note 928, 620 Page Mill Road, Palo Alto, CA.

[10] SHIMODA, K., "Ammonia Masers," IRE Trans. Instr. and Meas., IM-11. December 1962, pp. 195-200.

[11] WALLARD, A.D., J. Phys. E. 5, 927 (1972).

[12] See for example:
VIENNET, J., AUDOIN, C., and DESAINTFUSCIEN, M., "Discussion of Cavity Pulling in Passive Frequency Standards," Proc. 25th Annual Symposium on Frequency Control, U.S. Army Electronics Command, Ft. Monmouth, NJ, April 1971, pp. 337-342.

## LIST OF FIGURES

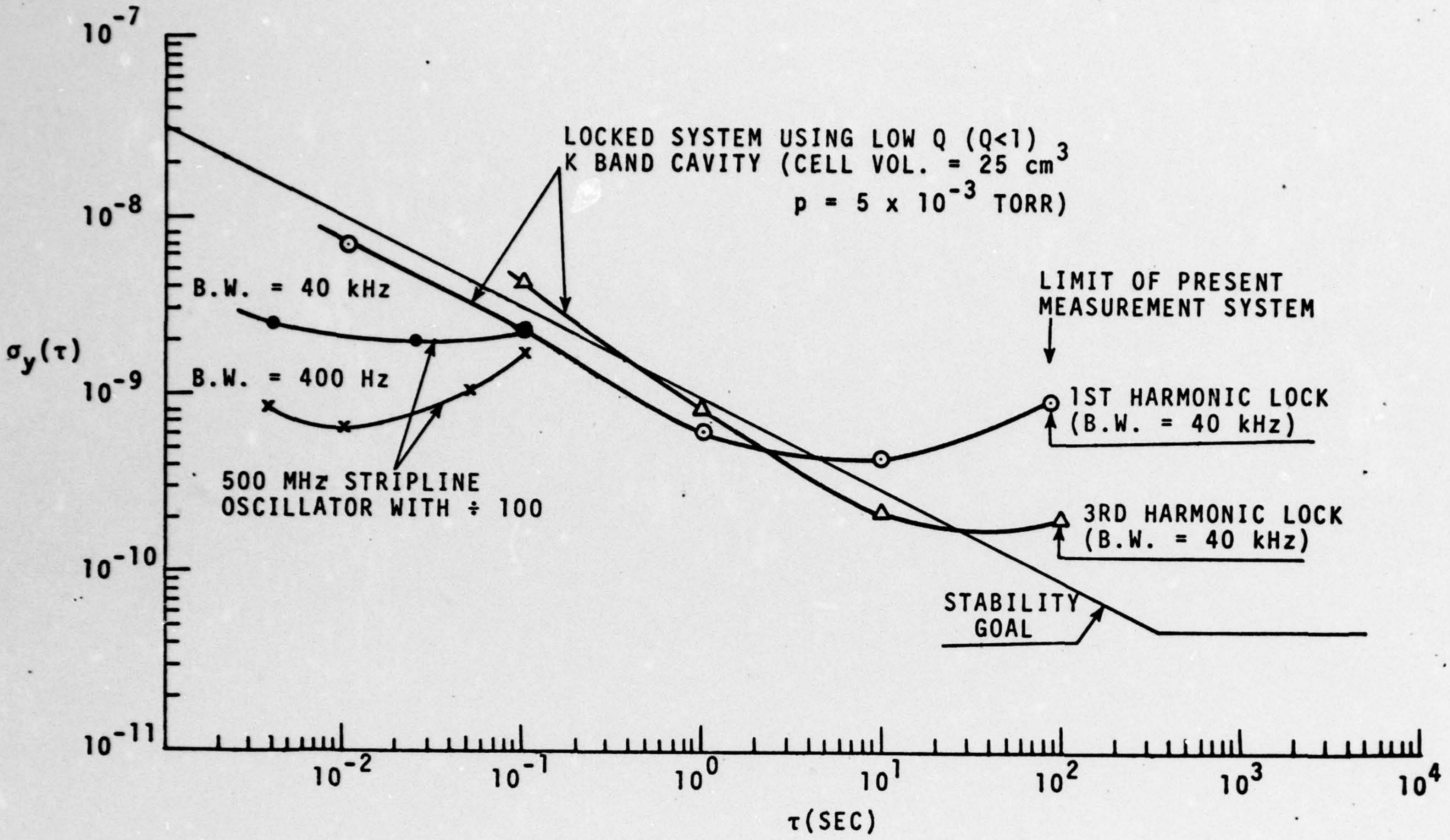

$10^{-7}$
$10^{-8}$
$10^{-9}$
$10^{-10}$
$10^{-11}$
$\sigma_y(\tau)$
$10^{-2}$
$10^{-1}$
$10^{0}$
$10^{1}$
$10^{2}$
$10^{3}$
$10^{4}$
$\tau$(SEC)
LOCKED SYSTEM USING LOW Q (Q<1)
K BAND CAVITY (CELL VOL. = 25 $cm^3$
p = 5 x $10^{-3}$ TORR)
B.W. = 40 kHz
B.W. = 400 Hz
500 MHz STRIPLINE
OSCILLATOR WITH ÷ 100
LIMIT OF PRESENT
MEASUREMENT SYSTEM
1ST HARMONIC LOCK
(B.W. = 40 kHz)
3RD HARMONIC LOCK
(B.W. = 40 kHz)
STABILITY
GOAL

Fig. 1

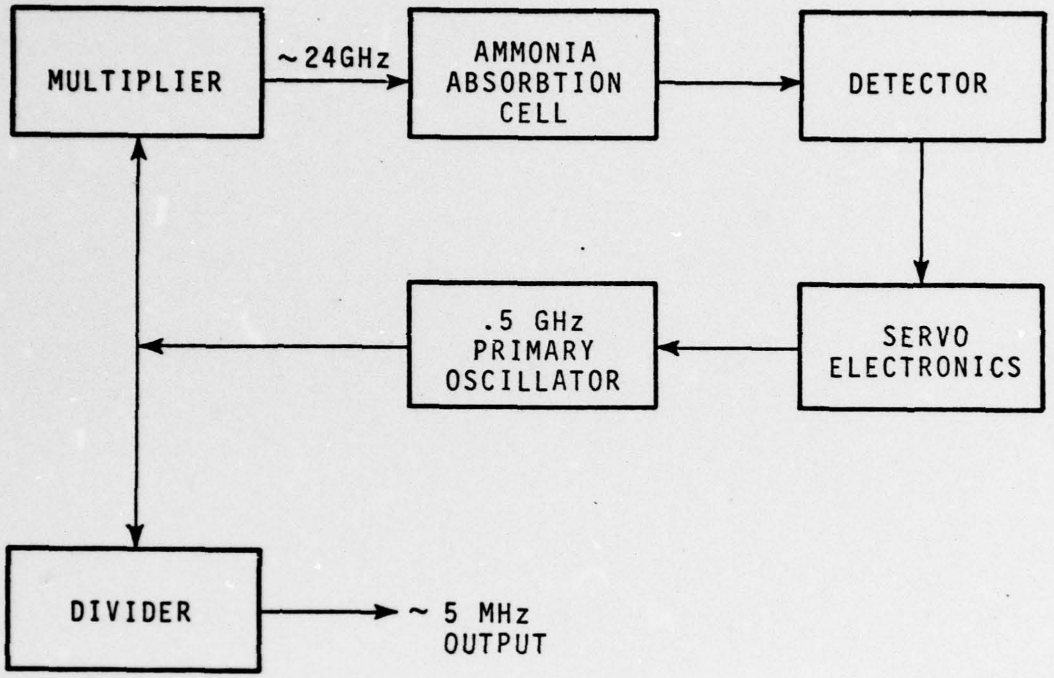

MULTIPLIER
~24GHz
AMMONIA ABSORBTION CELL
DETECTOR
SERVO ELECTRONICS
.5 GHz PRIMARY OSCILLATOR
DIVIDER
~ 5 MHz OUTPUT

Fig. 2

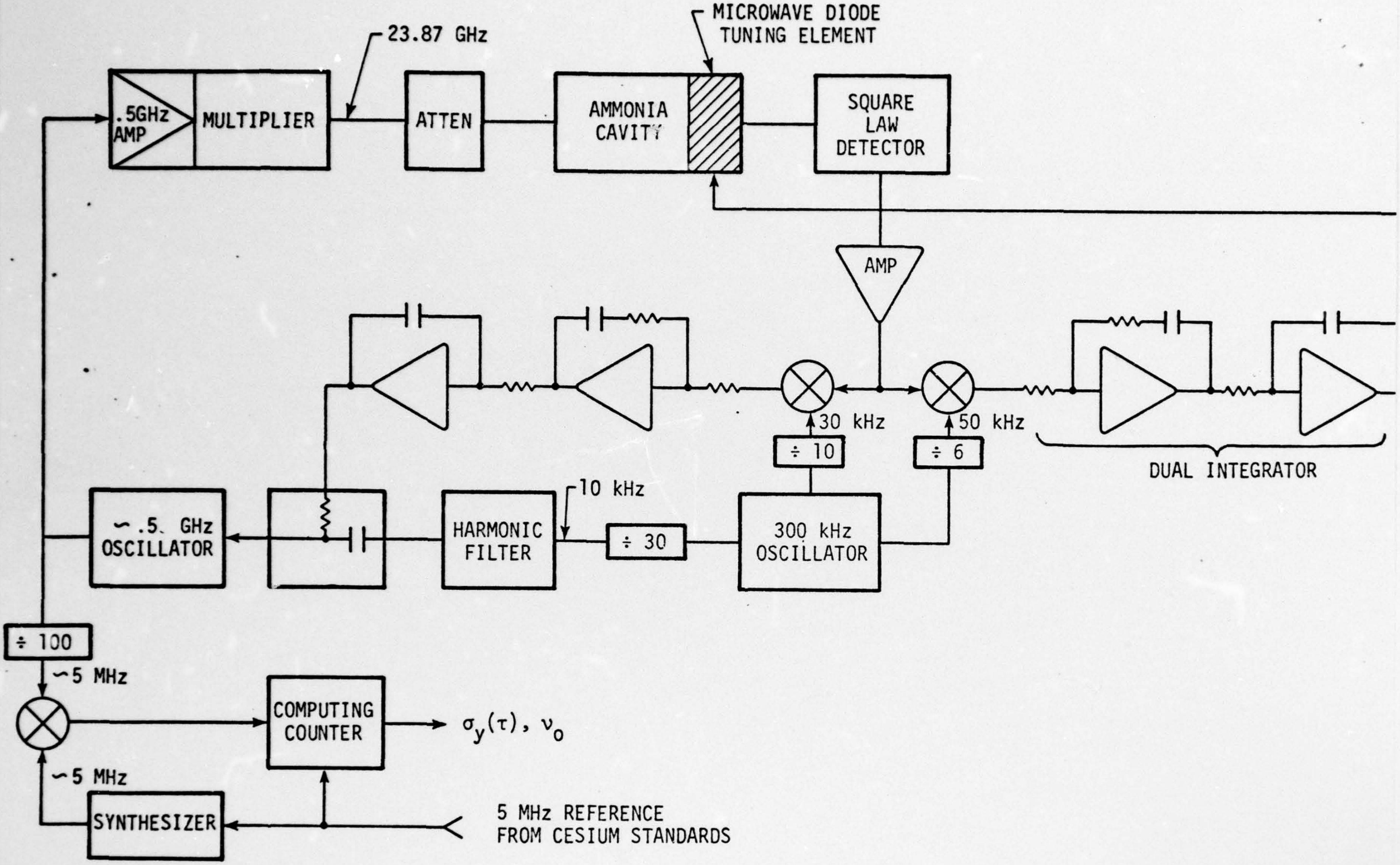
MICROWAVE DIODE TUNING ELEMENT
23.87 GHz
.5GHz AMP
MULTIPLIER
ATTEN
AMMONIA CAVITY
SQUARE LAW DETECTOR
AMP
30 kHz
50 kHz
÷ 10
÷ 6
DUAL INTEGRATOR
10 kHz
~.5. GHz OSCILLATOR
HARMONIC FILTER
÷ 30
300 kHz OSCILLATOR
÷ 100
~5 MHz
COMPUTING COUNTER
$\sigma_y(\tau)$, $\nu_o$
~5 MHz
SYNTHESIZER
5 MHz REFERENCE FROM CESIUM STANDARDS

Fig. 3

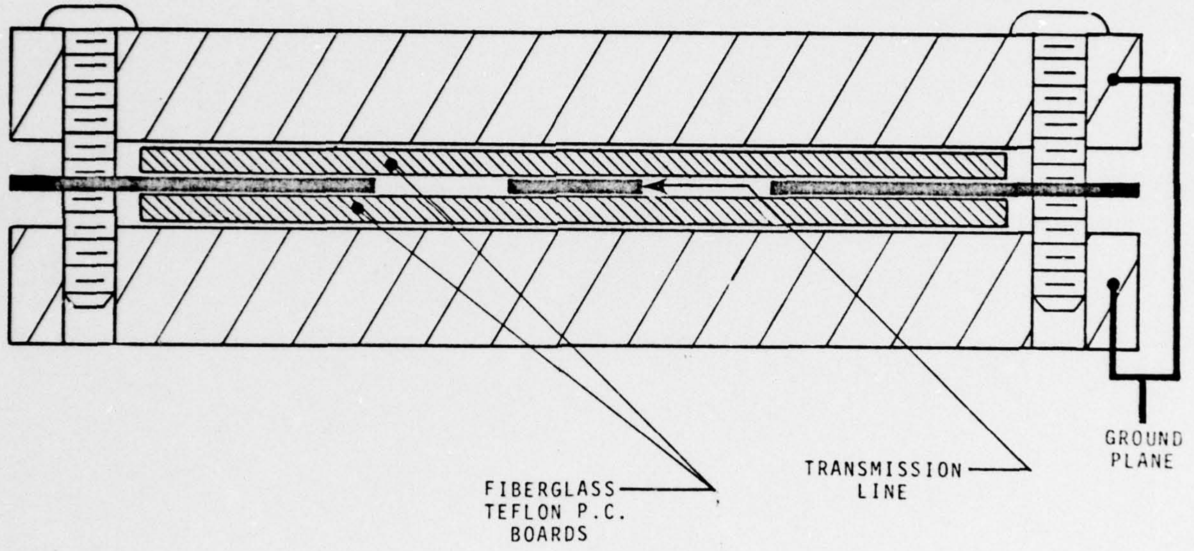

FIBERGLASS
TEFLON P.C.
BOARDS
TRANSMISSION
LINE
GROUND
PLANE

Fig. 4

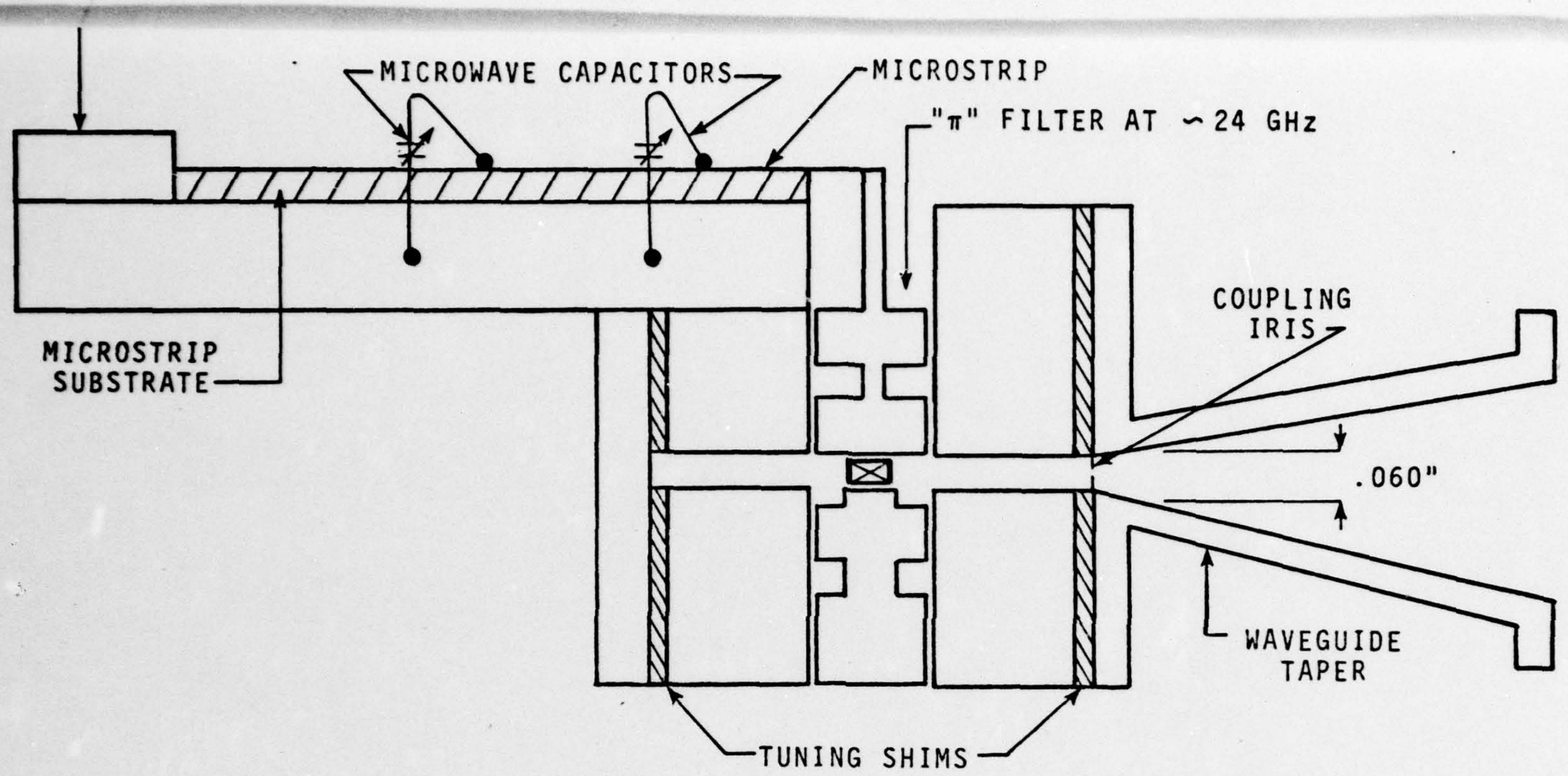

MICROWAVE CAPACITORS
MICROSTRIP
"π" FILTER AT ~24 GHz
COUPLING IRIS
.060"
WAVEGUIDE TAPER
TUNING SHIMS
MICROSTRIP SUBSTRATE

Fig. 5

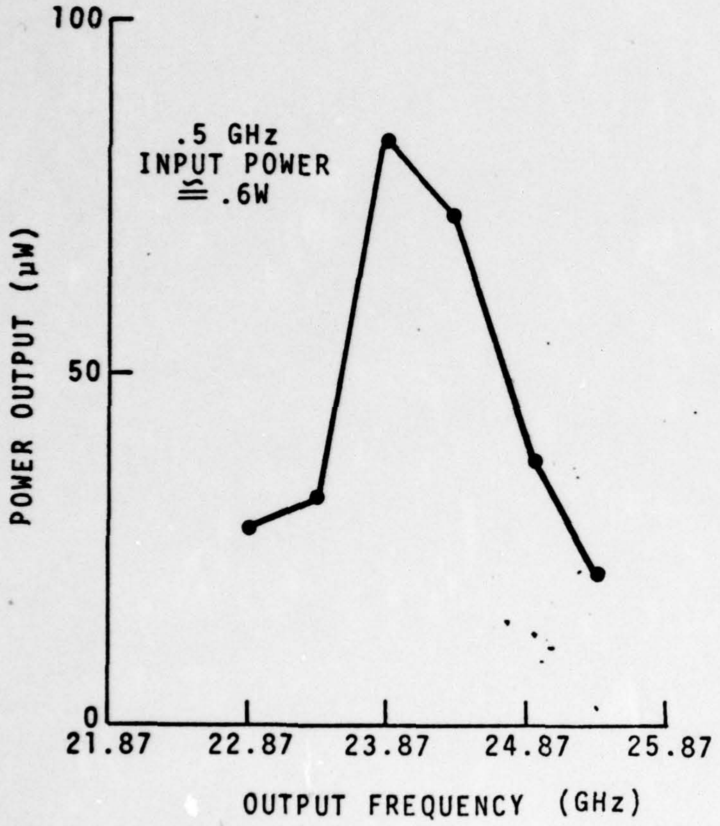
100
50
0
POWER OUTPUT (μW)
.5 GHz
INPUT POWER
≅ .6W
21.87
22.87
23.87
24.87
25.87
OUTPUT FREQUENCY (GHz)

Fig. 6

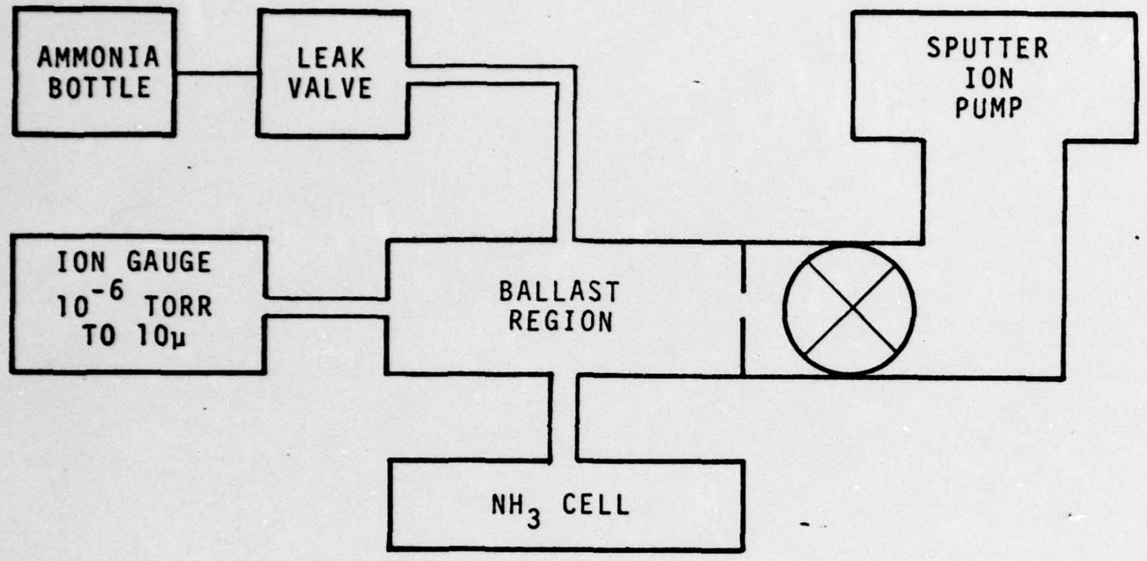
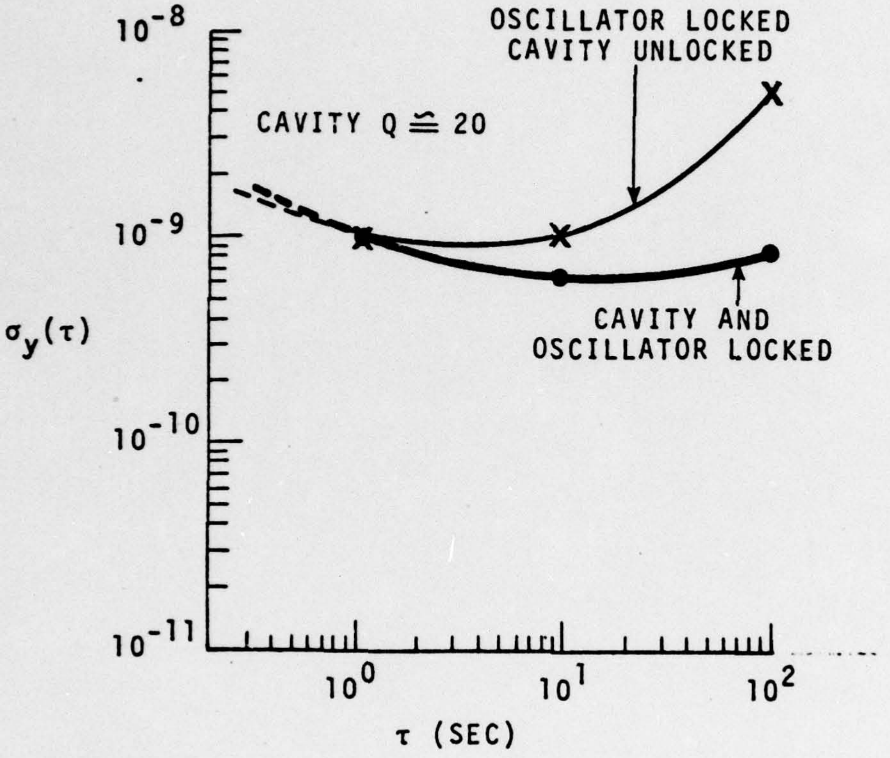

AMMONIA BOTTLE
LEAK VALVE
SPUTTER ION PUMP
ION GAUGE $10^{-6}$ TORR TO 10μ
BALLAST REGION
$NH_3$ CELL

Fig. 7



$10^{-8}$
$10^{-9}$
$10^{-10}$
$10^{-11}$
$\sigma_y(\tau)$
CAVITY Q ≅ 20
OSCILLATOR LOCKED
CAVITY UNLOCKED
CAVITY AND
OSCILLATOR LOCKED
$10^0$
$10^1$
$10^2$
$\tau$ (SEC)

Fig. 8