Characterization of an All-cryogenic Oscillator as a Stable Frequency Source

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ABSTRACT

An entirely cryogenic stable oscillator[1] has been constructed and preliminary evaluation is underway. The oscillator consists of a ruby maser stabilized by a superconducting resonator. A unique three-cavity coupling technique isolates the superconducting stabilizer cavity from the biasing magnetic field of the maser while simultaneously providing electromagnetic coupling between these same elements. This general design has been developed into a configuration that is particularly rigid with respect to physical, thermal and electromagnetic distortions. Maser oscillation at 2.69 GHz is developed by a 500 Gauss magnetic field, supplied by a superconducting magnet in persistent mode, and is stimulated by a 13.04 GHz pump signal. The maser operates at very low input power ($\approx 10^{-5}$W) with approximately a 2 K noise temperature. The stabilizer cavity consists of a solid sapphire spool onto which a superconducting film has been deposited.[2]

This system has been integrated into a ^{4}He cryostat capable of temperatures below 0.9 K. Frequency pulling effects caused by changes in pump amplitude, in pump frequency, in temperature and in magnetic field are being characterized. With a moderate system Q ($Q = 10^8$) the stability of the cryogenic oscillator exceeds that of our present rubidium reference oscillator. Using this reference, a stability of $\sigma_y = 3\times10^{-14}$ in 4000 seconds was measured, a value nearly identical to that obtained when calibrating the reference against a hydrogen maser. Stabilizing resonators with $Q > 10^9$ have been fabricated.

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1. Introduction

A joint effort by Caltech and JPL to develop a high-stability frequency source consisting of an all-cryogenic superconducting maser oscillator is being carried out at the Low Temperature Physics Laboratory at Caltech. Plans for the superconducting maser project were first described two years ago at PTTI 15. Significant changes have been made in the design outlined in that paper, and new results have been obtained. We are now operating such an oscillator and we shall report on results of these initial evaluation runs. We shall describe the present design and the ideas that lead to it. Also included is a discussion of projected performance of superconducting maser oscillators of different configurations and operating conditions. We shall also present new data on the performance of major components of the oscillator in various conditions.

2. Overview of the oscillator system

In reviewing previous efforts to utilize superconducting cavities in stable oscillators,[3,4,5] the difficulty associated with the varying length of the low temperature to room temperature transmission of the signal looms immediately. One can remove this length from the primary loop that determines the frequency of the oscillator by placing both the stabilizing cavity and the active electronic elements at low temperature. Additional benefits that result from an all-cryogenic design are reduced expansion coefficients for all electronic components (by as much as 10^6), improved temperature stability of the environment and the possibility of very low noise electronics.

A primary concern in this design is the stability of the superconducting cavity itself. Large quality factors (Q's) are commonly obtained[6] in such electromagnetic resonators, but responses to environmental influences cause variations in the resonant frequency of the cavities. These responses can be reduced by supporting the cavity-defining thin superconducting film on a substrate more stable against deformations caused by environmental disturbances.[7,8] We have chosen to use lead(Pb) for the superconductor and single crystal sapphire for the substrate. The high Debye temperature of sapphire gives an expansion coefficient more than 100 times smaller than that of lead or niobium. Because the Pb film encloses the sapphire into the resonant cavity, the absorption of the electromagnetic signal in the sapphire must be very low to allow high values of Q to be obtained. We have demonstrated[2] absorption coefficients in sapphire below 3×10^{-10} at temperatures near 1.5K. Such material has been used to form resonant cavities with a resonant frequency of 2.69 GHz and having Q-values greater than 10^9 at low temperatures (see Fig. 1).

The need for electronics that operate at low temperatures with low noise properties suggests the ruby maser.[9] Noise temperatures near ambient have been obtained in amplifier applications.[10] An added advantage of the maser is the low level of bias power required to operate it, reducing the burden on the cryogenic system used to cool the oscillator and allowing operation at lower temperatures. While little was known about the frequency-dependence of the noise in ruby masers, we have shown previously[1] and shall demonstrate further here that ruby masers can serve very successfully as the active element in a high-stability oscillator. To operate the ruby maser, a 13 GHz pump signal must be brought into the low temperature area of the oscillator and an ultra-stable magnetic field must be applied to the ruby to bias the energy levels to the proper splitting.

2.1. The Cryostat

The design of the cryostat was intended to obtain temperatures as low as possible while maintaining the simplicity of using only liquid ^{4}He as cryogen. A design placing a pumped pot of liquid helium inside a vacuum space which itself is surrounded by a bath of liquid helium at 4.2 K was considered adequate for the first oscillator system. A sketch of the contents of the vacuum space, i.e., the pumped pot (the "1K pot"), the three cavities and the superconducting magnet, is shown in Fig. 2. The pump line for the 1K pot, labelled "helium exhaust" in Fig. 2, provides a net pumping speed of 40 liters per second at the 1K pot. When connected to a large (64 l/s) laboratory mechanical pump via lines of 10 cm diameter, the 1K pot can be cooled to 0.84 K when no external heat load is applied. Temperatures as low as 0.86 K have been obtained during operation of the maser oscillator. The 1K pot is filled from the outer liquid helium bath through a valve and capillary (not shown in Fig. 2). The 0.5 liter volume of liquid helium in the 1K pot lasts about five days of normal operation at 1.0K, the helium loss being almost entirely due to incidental heat conduction by cryostat components and not due to oscillator operation. The outer liquid helium bath requires daily refilling in the present dewar.

2.2. Performance of Different Configurations

On the basis of the results obtained to date and on our analysis of the causes of instability in this system, we can predict several different levels of performance of similar systems according to their configuration and operating conditions. Fractional frequency fluctuations, internal to the oscillator, due to white noise in the ruby feedback amplifier are given by

$$\sigma_y^2(\tau)_{int} = \frac{kT_N}{2PQ^2\tau}$$

and those caused by the following amplifier's additive noise are given by

$$\sigma_y^2(\tau)_{add} = \frac{3kT_N B Q_{ext}}{8\pi^2 f^2 P Q \tau^2}$$

where

σ_y = Allan variance of measurements of y = Δf/f
k = Boltzman's constant
T_N = noise temperature of the amplifier
P = signal power generated in the oscillator
Q_{ext}, Q = external and loaded Q's of the resonator
τ = measuring time of the frequency sample
B = bandwidth of the frequency measurement.

As shown by the curve labeled E in Fig. 3, at short times the performance for almost all conditions is dominated by the noise in the following amplifier. The amplifiers in the present system have noise temperatures near 1000 K, but S-band amplifiers with similar gains (near 30 dB) and noise temperatures well below 100 K are readily available. On the other hand, if operated at power levels below 10 nW the short-time instability curve will be increased in proportion to $P^{-1/2}$ as shown in the preceding equation.

The performance at longer times will be dominated by fluctuations or drift in the temperature, mostly affecting the stabilizing cavity itself. For this discussion of effects of temperature variations, we model the temperature fluctuations as increasing by the one-fourth power of time from a value of $\Delta T = 3\times10^{-6}$K at one second. We can then plot the frequency instabilities caused by these fluctuations for the different cavity types operated at various temperatures. For example, curve A in Fig. 3 shows the instabilities for a solid niobium cavity operated at 1.25 K. Curve B, on the other hand, shows the frequency fluctuations expected for our Pb-on-sapphire cavity operated at 1.0 K with such temperature variations. Curves C and D demonstrate how improved performance might be obtained. By employing a dielectric cavity, e. g., an all-sapphire resonator with no superconducting coating,[11,12] the only response to temperature changes is the expansion of the cavity, so even at an operating temperature of 1.25 K a stability of 10^{-17} can be achieved at 100 seconds measuring time, and stability below 10^{-16} can be maintained for rather long times, as shown in curve

C. Similar frequency stabilities should be demonstrated by our Pb-on-sapphire cavity if operated at a temperature of 0.8 K. If the operating temperature of the Pb-on-sapphire cavity is lowered to 0.6 K, its response to temperature changes will also be dominated by the expansion effect, so at 0.6 K both the Pb-on-sapphire and the all-sapphire cavities should approach stabilities near 10^{-18} for measuring times near 1000 seconds.

No doubt, perturbations other than temperature changes or other expansion effects will cause frequency fluctuations larger than the smallest of those depicted in Fig. 3 and will need to be dealt with to allow the very stable performances predicted. Such perturbations and their effects can be reduced as their nature allows to obtain optimum stability.

2.3. Choice of Oscillator Elements

Selection of the type of cavity to employ will be influenced by the stability goal and by the type of cooling that is available. For example, if the experimenter desires to use the simple cryogenics of a continuous flow ^{4}He system that will operate near 1.25K,[13] then according to the discussion of the preceding section the all-sapphire cavity would seem to be the best choice of cavity type, producing stabilities as low as 10^{-17}. If, on the other hand, the experimenter wishes to obtain much better stability levels, then cooling to lower temperatures is necessary and the all-sapphire cavity offers no advantages over the superconductor-coated sapphire cavity. Considerable development must precede the use of all-sapphire resonators to determine their applicability to these oscillator systems. For example, the most appropriate shape must be found, and a suitable coupling technique must be devised.

A second oscillator element to be considered is the active element of the system. The high electron mobility solid state devices (HEMT's) show promise as the active elements in cryogenic oscillators. Noise temperatures of 2 K have been measured at S-band frequencies for these devices used in amplifiers.[14] Once again, since the frequency dependence of the noise has not been determined for HEMT's, their suitability to oscillator application has yet to be demonstrated.

An additional important feature for the HEMT's and for other coolable solid state devices is the power required to bias these devices into the best operating region. Powers in the range one to fifty milliwatts are generally required for the amplifier applications of these devices.[14,15] In contrast, we have operated our ruby maser oscillator with only ten microwatts of RF bias power. Such low powers can be crucial both to operation at lower temperatures and for operating over long periods. For example, using only the latent heat of liquid helium at 1.0K, ten microwatts will evaporate a liter of liquid helium in nine years.

3. Oscillator Design

The three-resonator oscillator, shown in Fig. 4 and schematically in Fig. 2, is designed to allow a physical separation between the ruby resonator (Fig. 5), which requires a magnetic field of 500 Gauss for maser operation, and the stabilizing superconductor-on-sapphire resonator (Fig. 1), whose performance would be greatly degraded by such a field. This separation is provided by a $3\lambda/2$ coaxial coupling resonator. Successful operation of the oscillator requires that sufficient energy be coupled from the stabilizing resonator to the negative resistance of the ruby to allow oscillation, while supressing oscillation in the other modes of the system. A description of the method used to calculate the modes and Q's of the oscillator has already been presented.[1] We present here details of the design procedure used to select the 5 parameters (3 frequencies and 2 coupling constants) which characterize the oscillator.

The general features of the selection process can be understood from Figure 6. The resonant frequencies of the coupled cavity system, ω_α, ω_β, and ω_γ, represent modes with energy principally in the ruby, coupling, and stabilizing cavities, respectively. Each mode actually has some energy in each of the three physical resonators, and the tendency of a given mode to oscillate is enhanced by its Q, by the fraction E_r/E of its energy in the pumped ruby, and by the (negative) Q of the ruby at the mode frequency. All other things being equal, oscillation will naturally occur first in the mode with most of its energy in the ruby-filled resonator. This mode of oscillation must be prevented and instead, the stabilized mode, with nearly all of its energy in the sapphire resonator, must be excited.

The frequency dependence of the regenerative power of the ruby, shown as the solid curve in Fig. 6, allows selection of this desired mode of oscillation. Operation in the unwanted modes is prevented by tuning the center frequency of the ruby gain, by adjustment of the 500 Gauss bias field, sufficiently far from the frequencies of the other two modes so that the (negative) Q of the ruby has larger magnitude than the mode Q's at their resonant frequencies. Under this circumstance, the Q's of the unwanted modes will be enhanced by the ruby, but oscillation is prevented.

Quantitatively, the bars in Figure 7 represent the loss rates in the three modes multiplied by the fraction of mode energy in the ruby cavity, and the curve represents the gain of the ruby. Under steady-state oscillating conditions, losses exactly equal gains, as shown for the stabilized mode γ. In the other two modes as shown, half of the losses would be overcome by the regenerative effect of the ruby, thus doubling their Q's. Mode β, with relatively less of its energy in the ruby-filled cavity, is less prone to oscillate than is mode α, and can thus be placed closer to the operating frequency ω_γ.

On the basis of our experience with the copper resonators that we have used so far in our study, we estimate the Q's of modes α and β to be about 3000. The Q of the stabilizing resonator is much larger than the Q's of the other two, and resulting values are shown to scale with this Q. Based on our previous results with the low Q ruby oscillator[1], we estimate that , in a 90° orientation, and operating between levels 3 and 4 at approximately 500 Gauss and 2.7 GHz,[16] the ruby's Q is approximately -400 with a bandwidth of 3.8%.

Calculations were performed in which the frequencies of modes α and β were varied until their Q's were doubled, based on an assumed Gaussian line shape for the ruby. Figure 7 shows the frequency offsets as calculated for modes α and β with respect to the frequency of the stabilized mode γ. Values are plotted as a function of ruby bandwidth and for several values of the free parameter E^{γ}_{21}, the ratio of the energy in the coupling cavity to the energy in the ruby cavity for the stabilized mode γ; a value of 1.0 was chosen for the design as constructed. Figure 8 shows the coupling constants as a function of the same parameters.

Design considerations balance the required large values for coupling constants against the safety of very strong mode selection. An overly conservative (large) design value for the ruby bandwidth, giving little enhancement to the Q's of modes α and β, would result in increased sensitivity of the operating frequency to fractional changes in coupling, and eventually, to a breakdown of the weakly coupled model.

4. Results of Measurements

Our measurements have been directed toward determining the behavior of the oscillator system, especially its response to perturbing influences. The ability of certain system parameters to cause frequency shifts, frequency pulling effects, have been discussed previously and were characterized for the low-Q system assembled earlier.[1] The predicted reduction of these frequency pulling effects with increase of Q has been tested by repeating the measurements on the high-Q system currently under study.

The fractional frequency shift with change in the magnetic field,

$$\frac{\partial f}{f} = 2.5\times10^{-3}\times\frac{\partial H}{H}$$

found for a Q of 5000 becomes, at a Q of 10^8,

$$\frac{\partial f}{f} = 10^{-8}\times\frac{\partial H}{H}$$

The reduction is more than ten times the expected reduction from the increase of Q, probably reflecting improved field uniformity in the region of the ruby. To obtain stability levels of 10^{-15} or 10^{-17} with a system Q of 10^9, the magnetic field need be stabilized only to a part in 10^6 or 10^8, respectively, both of which are easily manageable with superconducting magnets and magnetic shields.

The second frequency pulling effect of some concern is the amplitude of the 13.04 GHz pump signal that excites the ruby maser. In the low-Q oscillator, one decibel (dB) change in pump power caused a fractional frequency shift of 5×10^{-8}. In the high-Q system, the value measured is 2.5×10^{-12}, scaling exactly with the change in Q value. This result implies that to obtain a stability level of 10^{-15} with a system Q of 10^9, the pump power will need to be stabilized to .004 dB, a readily achievable task. The requirement of 4×10^{-5} dB power stability to obtain 10^{-17} frequency stability is more of a challenge. It is possible that further improvement of the magnetic field uniformity in the ruby region will reduce this requirement.

Analysis of the oscillator's performance and optimization of the operating parameters is based also on the measurement of Allen variance data for the fractional frequency stability at selected measuring times. Our setup for making and recording the repeated frequency measurements required for the Allen variance analysis is shown in a block diagram in Figure 9. The most unusual element there is probably the Hewlett-Packard HP 934A harmonic mixer, where the 27th harmonic of the synthesizer output is mixed with the 2.69 GHz signal of the superconducting cavity maser oscillator to produce an output signal of a few Hertz frequency. This much lower frequency is measured and recorded in the data acquisition system.

The Hewlett-Packard HP 5065 rubidium frequency source is a special model of exceptional frequency stability. Its Allen variance performance curve, as measured versus a hydrogen maser oscillator, is shown as a solid line in Fig. 10. The stability performance of our Ailtech synthesizer and the harmonic mixer, again charcterized using a hydrogen maser oscillator, are also shown in the figure, as is the measured error in the data gathering system. The points plotted on the figure show the performance of our oscillator in two different configurations of different Q-values and, for comparison, that of another superconducting cavity oscillator. Note that the high-Q configuration of our oscillator shows data matching that of the rubidium measured versus the hydrogen maser; no better values can be measured with this measuring system. These data demonstrate that the all-cryogenic oscillator performs with better stability than the rubidium source for all the range of measuring times studied.

To actually characterize the superconducting cavity maser oscillator's Allen variance of frequency fluctuations, a better comparison oscillator must be used. The second superconducting cavity oscillator was acquired for this purpose, but problems have occurred with the cryogenics of that system that have prevented our making this comparison to this date. Work is proceeding toward this end.

5. Summary and Conclusions

Our previous work has shown that Q's greater than 10^9 can be obtained in sapphire-supported superconducting resonators, and that a ruby maser shows very low noise in oscillator applications. A design has now been implemented which allows a superconducting resonator and a ruby maser amplifying element to be combined in an all-cryogenic stabilized oscillator. First and second tests of the oscillator were conducted with loaded Q's of 10^7 and 10^8, respectively, by varying the coupling between the ruby and superconducting resonators. The results of these tests show that, so far, instabilities and frequency pulling effects scale with the loaded Q. At a Q of 10^8 the stability for all measuring times was better than that of our reference oscillator, a specially selected rubidium frequency standard.

On the basis of measured resonator and maser parameters, a stability of 1×10^{-16} should be possible for the Pb-sapphire stabilized oscillator at 1.0K and 1×10^{-17} at 0.8K. Without installation of the cryogenic isolator, and with the relatively noisy follower amplifier presently being used, our results extrapolate to a stability of approximately 1×10^{-15} for a Q of 10^9.

Power input to the oscillator during operation was approximately 1×10^{-5} watts. This small power raises the prospect of very long term unattended oscillator operation since, if absorbing only this power level, a one liter tank of helium would last approximately nine years without refilling.

6. Acknowledgements

The authors wish to acknowledge the assistance of Mark Friesen on the calculations of the design parameters of the three-cavity oscillator configuration. Ed Boud provided valuable technical assistance for the assembly of the cryostat and the cavities.

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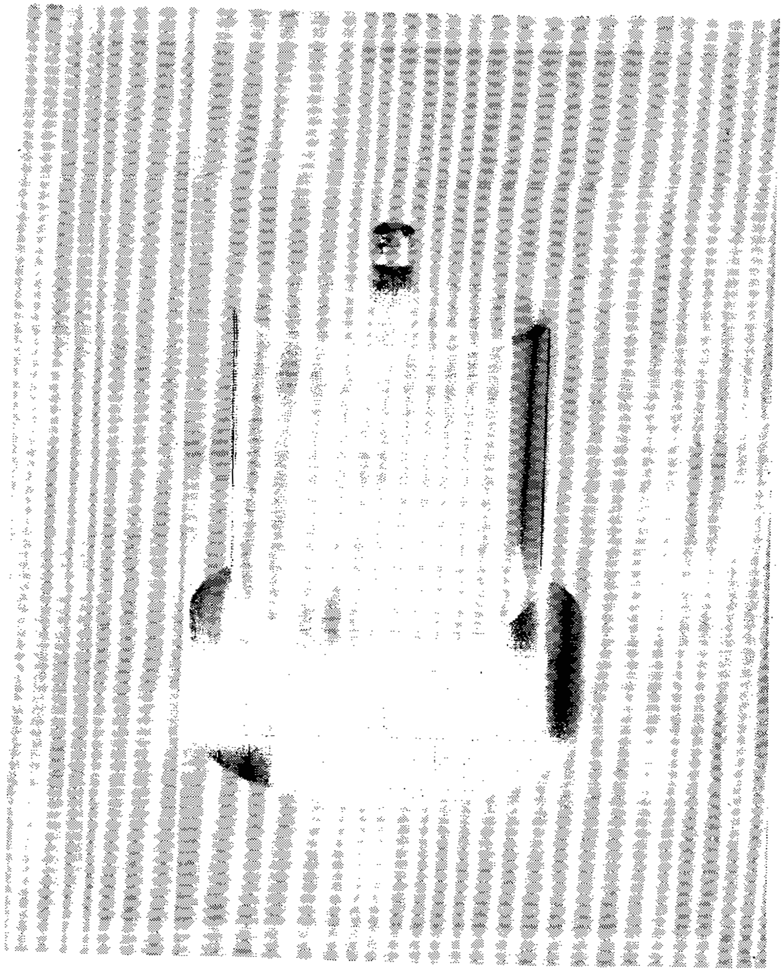

Figure 1

Lead-On-Sapphire resonator with mounting plate

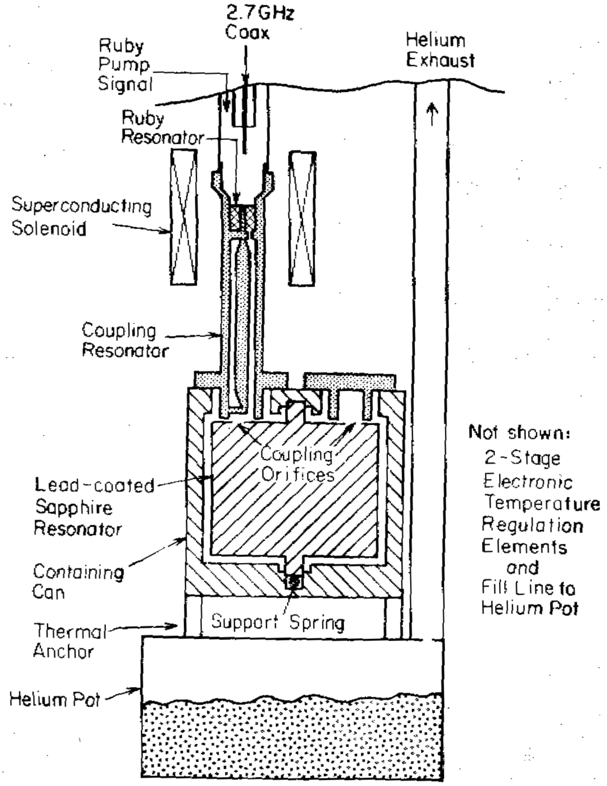

Figure 2

Schematic diagram of three-cavity oscillator and cryogenic components

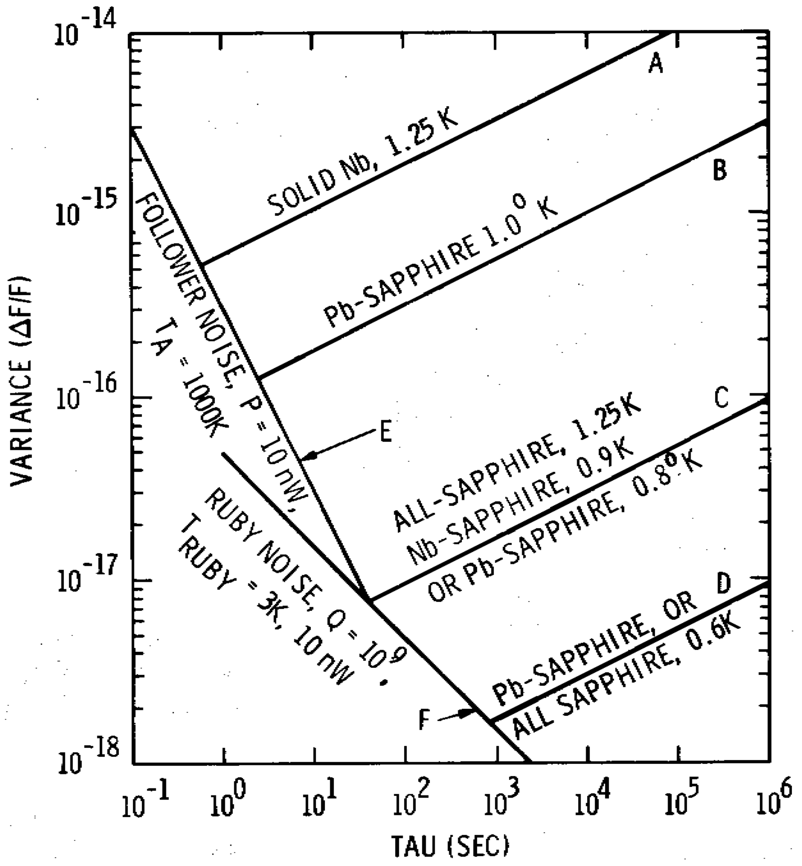

Figure 3

Performance capability of oscillator for various stabilizing cavity technologies and different operating temperatures

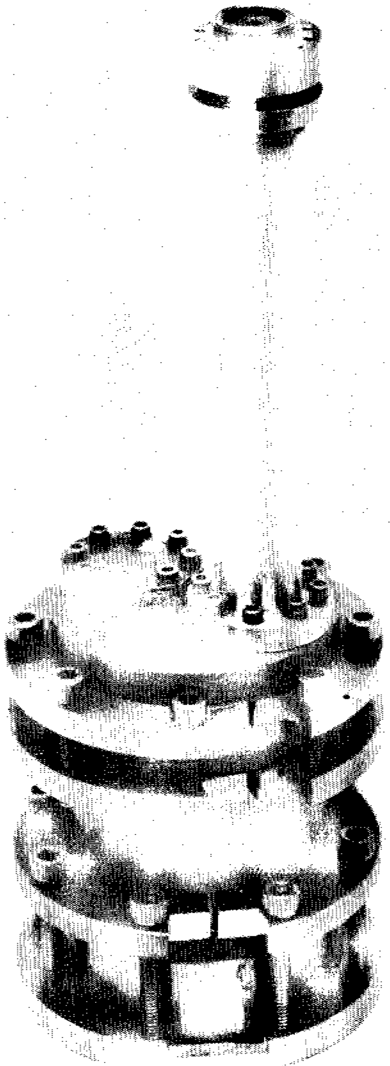

Figure 4

Three-cavity oscillator assembly

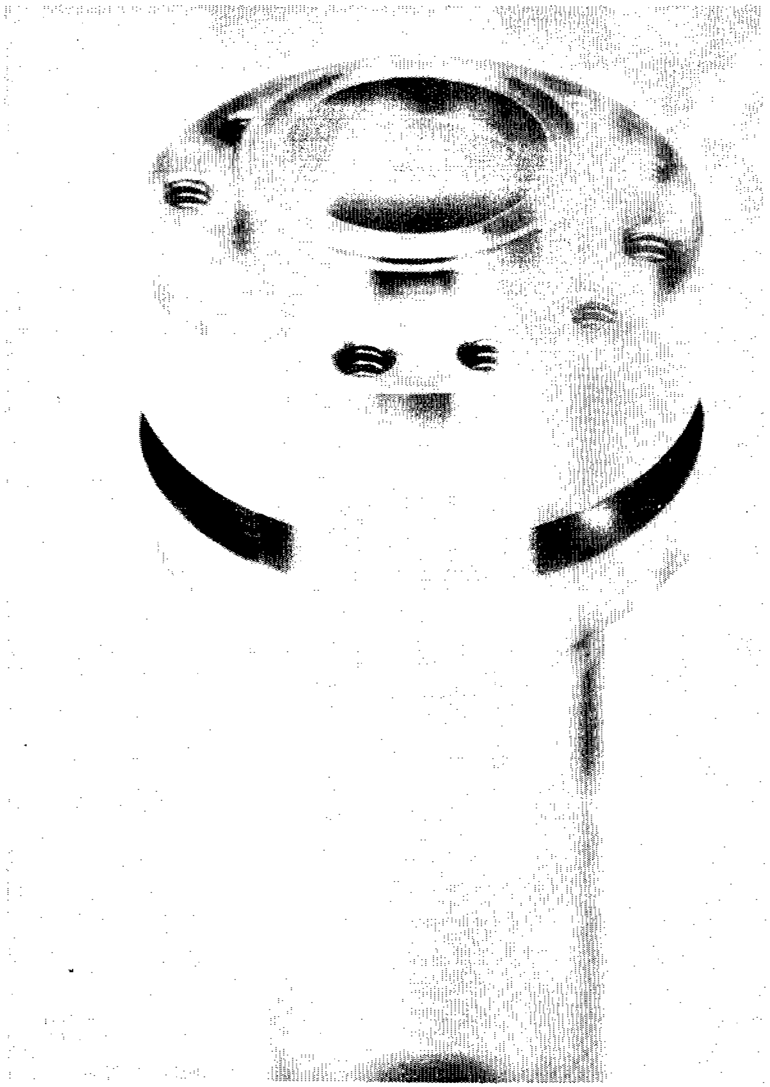

Figure 5

Ruby detail, oscillator assembly

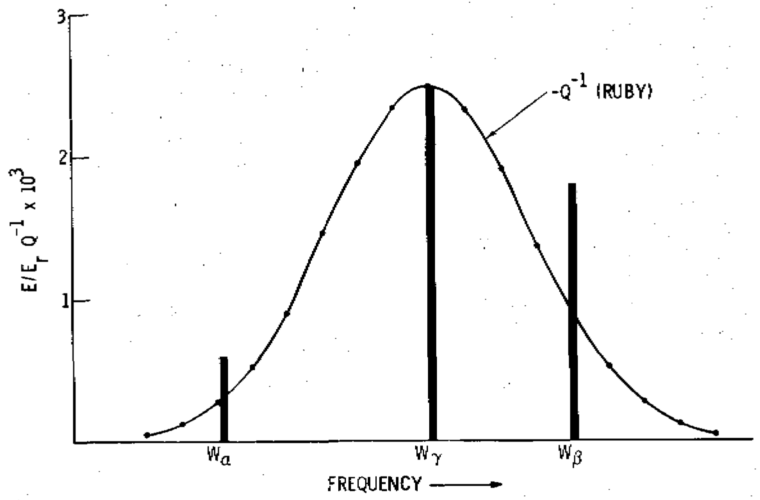

Figure 6

Mode selection graph. Ruby gain compared to mode loss for the coupled resonator system.

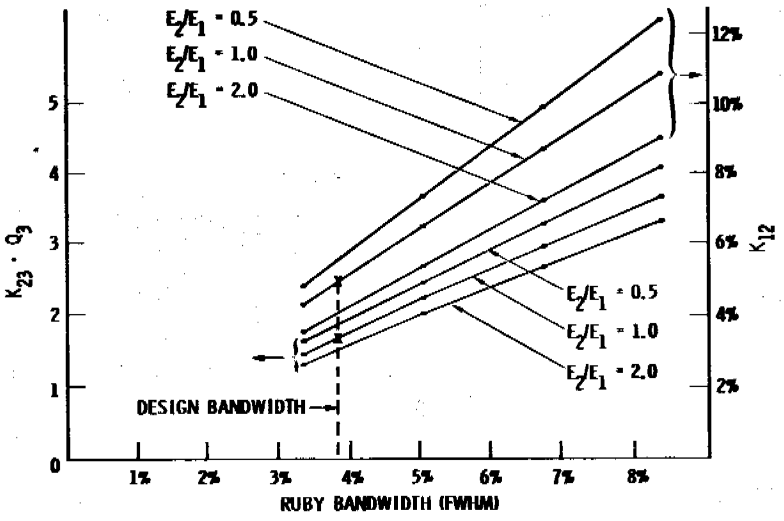

Figure 8

Coupling constants for various design conditions. Same parameters as Figure 7.

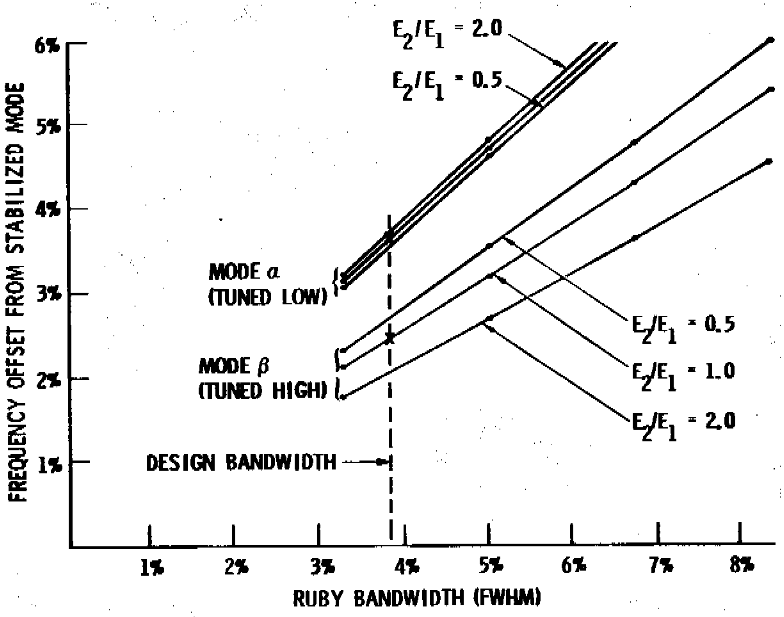

Figure 7

Mode frequencies for various design conditions. $Q_{ruby} = -400$, $Q_\alpha = Q_\beta = 3000$, marginal oscillation in mode γ, Q_α, Q_β enhanced two times.

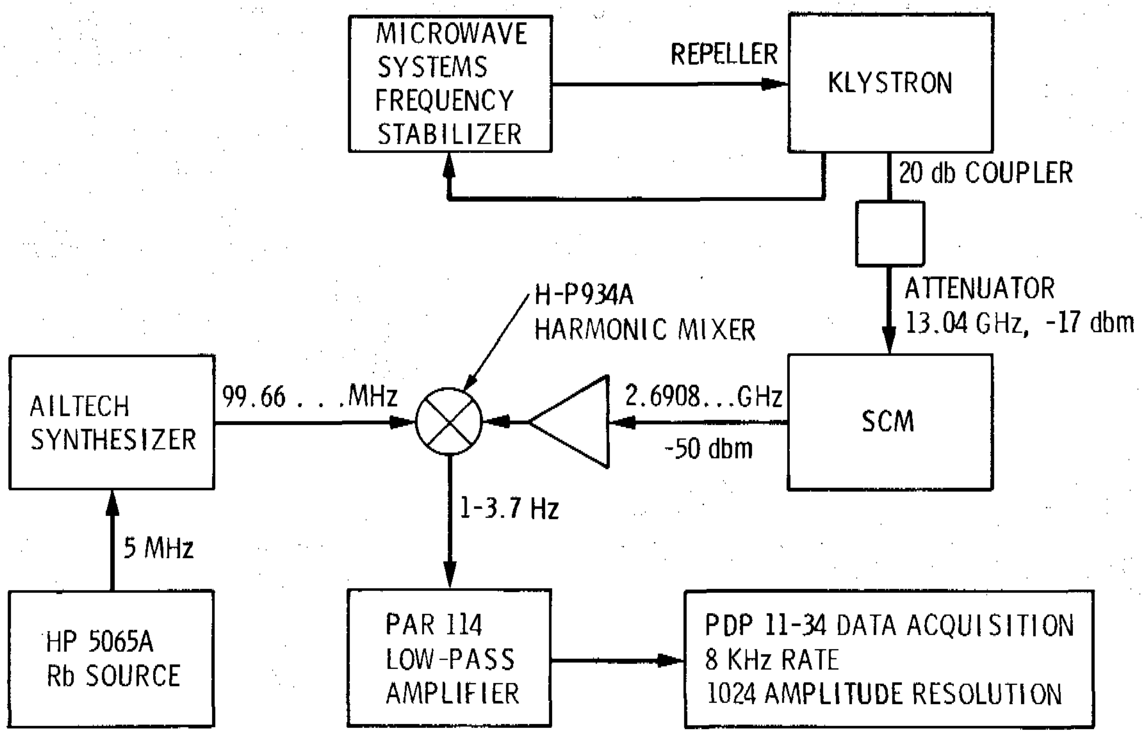

Figure 9

Block diagram showing data gathering setup

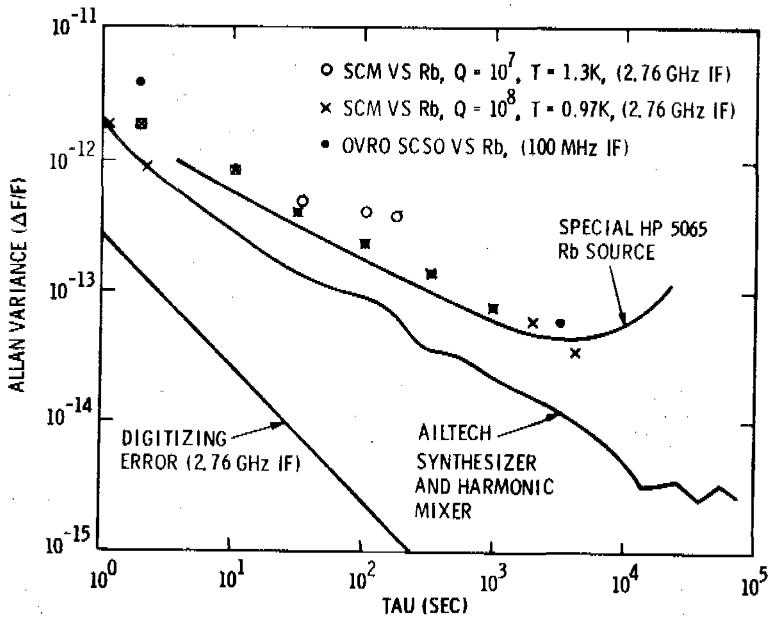

Figure 10

Plot of performance of all-cryogenic oscillator using Rb frequency source as reference. Measured performances of the various elements of the data-taking setup are also shown. Similar test of niobium-cavity SCSO included for reference.

QUESTIONS AND ANSWERS

CARROLL ALLEY, UNIVERSITY OF MARYLAND:
Those are very interesting results. Could you compare your work briefly with that of Vladimir Braginski? He has been talking about this kind of thing for many, many years.

MR.DICK:
Yes, I have talked with him about it. He and David Blair in Australia and we all get Q's of ten to the ninth in open sapphire resonators. Braginski has been working with the whispering gallery modes in open resonators. His resonators are typically big. They don't look like ours. They are about this big around (indicates a number if centimeters in diameter) and sort of flat. He then has a very high order mode around the periphery. He hasn't really tried for a high stability, long term sort of oscillator. They have mostly concentrated on low noise oscillators, mainly from the point of view of gravitational wave detection. Both he and David Blair have pursued it from that point of view, using tunnel diodes and FET's , both of which are much noisier components than what you really need. We looked at GAsFET's but their high multiplicative 1/f noise kept us away from them in this application, even though they have a low noise temperature. Having access to the ruby maser technology at JPL was the reason that we went into this. The group there makes amplifiers with noise temperatures of two degrees so we could use that technology for our oscillator.