The Superconducting Cavity Stabilized Ruby Maser Oscillator

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ABSTRACT

We present an analysis of the stability, performance, and design of a new all-cryogenic frequency source, the superconducting cavity stabilized maser oscillator (SCSMO).[1] We also present the results of an experimental study of the various components of such an oscillator which demonstrate the feasibility of achieving a stability better than $\Delta f / f = 10^{-17}$ with this technique.

Previous superconducting cavity stabilized oscillator designs have combined solid niobium cavities at cryogenic temperatures with room temperature microwave electronic components to achieve the highest stability reported to date,[2] $\Delta f / f = 3 \times 10^{-16}$. The long term performance of these designs suffers due to instabilities in the connecting link between electronics and cavity. A successful all-cryogenic design would eliminate this problem due to the "freezing-out" of thermal expansion coefficients and a complete avoidance of temperature gradients.

The ruby maser currently allows the lowest noise temperature (1.5K) of any microwave amplifier and seems an ideal component for an all-cryogenic oscillator. The power available ($\sim 10^{-7} W/cm^3$ at 4.2K) is adequate for measuring times longer than one second, and the gain ($Q_m = -100$) is large enough to allow oscillation with very weak coupling to the stabilizing cavity. Furthermore, power dissipation is very low, allowing operation in the same cryogenic environment as the cavity even at temperatures below 1K. The magnetic field required for maser operation and tuning gives rise to important technical problems, namely, the need to shield the superconducting cavity from the field, and frequency-pulling effects as the field varies. We present an analysis of a multiple-

cavity design which allows the active ruby element to be physically removed from the superconducting cavity. We shall also show maser oscillator stability using a relatively low-Q normal stabilizing cavity where pulling effects are greatly enhanced.

Finally, we will present the results of our work to obtain a superconducting cavity with the highest possible mechanical integrity. Sapphire has a thermal coefficient of expansion 100 times less than niobium and sags 10 times less in the earth's gravity. We have obtained the lowest microwave loss values to date in sapphire (7×10^{-10} at 1.5K) and have demonstrated a superconductor-on-sapphire resonator with $Q = 10^8$, the value required by our design.

1. Design of the SCSMO

1.1. General Features of an All-Cryogenic Oscillator

The two techniques for highest frequency stability are combined in the SCSMO to allow an all-cryogenic oscillator. Superconducting cavity stabilized oscillators (SCSO's) to date show great cavity stability due to very low cavity losses and the freezing out of thermal expansion coefficients at cryogenic temperature, but phase shifts in the cryogenic transition and room temperature electronics limit attainable performance. Hydrogen masers have great stability in the atomic transition itself, but frequency pulling effects due to the high-Q cavity required to induce oscillation introduces drift, and the low power available limits short time performance. Long time instability, in both cases, is due to frequency pulling effects within the bandwidth of the high-Q (10^8 to 10^{10}) stable element, and appear to be principally due to thermal expansion effects in supporting electronic elements. Since overall stability of 10^{-15} to 10^{-17} is desired, the performance required of support components is very high, since these values are 10^{-5} to 10^{-9} of the natural bandwidth of the stabilizing element.

In both cases, the situation is worse than it might seem. In order to obtain oscillation with the low hydrogen densities allowed by the technique, a high-Q (normal) cavity is necessary for the operation of the hydrogen maser. Sensitivity to the cavity frequency is increased proportional to its Q, which is typically 10^4. Very stable materials and techniques of "auto-tuning" are used to reduce this sensitivity, but it continues to be a principle roadblock to improved performance.

Thermal effects in the SCSO are similarly exacerbated by two effects. The wavelength at the typical operating frequency (10 GHz) is much shorter than the path length required between room temperature electronics and the cryogenic cavity. This increases the sensitivity of the frequency to the fractional length change by 2π times the one-way length divided by the wavelength, a value typically about 10^2. Secondly, the waveguide must span a temperature differential of 300K, and thus small fractional changes in the temperature profile imply large temperature changes. To achieve a stability of 10^{-7} times the superconducting bandwidth, an average stability of 3×10^{-6} in the temperature profile is required. Electronic feedback techniques have been used to sense the instantaneous length in order to provide substantial compensation of this effect, with reported results of 3×10^{-16} overall stability, the best to date for any technique.[2] However, the overall system is cumbersome and expensive, and dramatic improvements seem unlikely.

The reduction in expansion coefficient of a superconducting cavity at low temperature together with its high Q make possible its use as a frequency stabilizing element. Niobium and copper have an expansion coefficient of $\sim5\times10^{-11}/K$ at 1.0K, a value reduced 10^5 from their room temperature values. Together with the short thermal relaxation times (10^{-3} seconds) and accurate temperature control ($10^{-6}K$) possible only at low temperatures, unparalleled structural stability can be achieved. The advantage of an all-cryogenic oscillator is that coefficients of expansion for the entire system are reduced, not just that of the cavity itself. This reduction eliminates frequency pulling effects which are due to thermal instability, the major source of drift in both H-maser and SCSO systems.

1.2. Application of the Ruby Maser

Ruby maser amplifiers are the quietest amplifiers presently available in the microwave frequency range, with device noise temperatures as low as 1.5K reported.[3] They operate naturally at temperatures below 4K, and can provide output power of a fraction of a microwatt, a value sufficient for excellent short term measurements and far above the 10^{-11} watts available from the H-maser. Furthermore, the pump power required is related only to the signal power, allowing very low power dissipation and consequently lower temperature operation, if desired. This is in contrast to the available transistor amplifiers which must dissipate several milliwatts of power in order to maintain their operating point.[4] Operation well below 1K seems feasible, with important consequent reductions in thermally generated frequency shifts in the superconducting cavity itself.

In contrast to the H-maser with its fractional linewidth of 10^{-9}, ruby has a fractional bandwidth of about 10^{-2}, making it unsuitable for determining the frequency itself. However, this wide bandwidth (low Q) is a distinct advantage when used in conjunction with a superconducting cavity, since it results in a reduction of frequency pulling effects. Frequency pulling of the actual operating frequency Δf_0 due to frequency change Δf_c in a lower-Q circuit element is proportional to the ratio of its Q to that of the frequency stabilizing element.

A comparison between frequency pulling effects in the two devices is instructive. While the H-maser's output closely follows the frequency of the masing transition, the sensitivity to its cavity frequency is given by

$$\frac{\Delta f_0}{\Delta f_c} = \frac{Q_c}{Q_m} = \frac{10^4}{10^9} = 10^{-5} \qquad (1)$$

for a cavity $Q_c = 10^4$ and masing linewidth characterized by $Q_m = 10^9$. In a similar manner, the frequency of the output of the SCSMO closely follows that of the high-Q superconducting cavity, while its sensitivity to the ruby resonant frequency f_m is

$$\frac{\Delta f_0}{\Delta f_m} = \frac{Q_m}{Q_c} = \frac{10^2}{10^9} = 10^{-7} \qquad (2)$$

for masing linewidth characterized by $Q_m = 10^2$ and a cavity $Q_c = 10^9$. It is apparent that the roles of the masing and cavity Q's are reversed.

We expect that the role of this source of frequency pulling will be much less significant in the design of the SCSMO than in the H-maser because of the reduction implied by equations (1) and (2), but more importantly because superconducting magnets allow great stability to be achieved in the applied magnetic field which determines the ruby resonant frequency. Long term stability of better than 10^{-12} has been reported at the relatively low magnetic fields required for masing action, which would imply, from equation (2), frequency drifts less than 10^{-19} from this source.

The magnetic field applied to the ruby must be effectively shielded from the superconductor of the stabilizing cavity, as Q degradation would otherwise result. The ruby material is very strongly amplifying, in comparison to what is needed to induce oscillation at a Q of 10^9, being able to excite a fully filled cavity with a Q of only 100. Thus it is possible to physically separate regions of high Q and high magnetic field - - conceptually, the ruby need only probe the fringe fields of the stabilizing cavity.

1.3. Superconducting Cavity Design

With the promise of much greater electronic stability allowed by an all-cryogenic design, the relationship of cavity Q to the overall design changes somewhat compared to the SCSO. In particular, a lower Q might be advantageous if it allowed substantially higher frequency stability to be attained in the cavity itself. This appears to be possible by the use of a superconductor-on-sapphire resonator when operated at temperatures somewhat lower than has been previously employed. While the thermal coefficient of expansion of solids follows a T^3 dependence, the penetration depth of the superconductor, which also determines the effective size of the resonator, shows a much more rapid exponential temperature dependence. Thus, for a solid niobium cavity, the frequency variation with temperature decreases rapidly as the temperature is reduced down to a temperature of approximately 1.25K, below which the relatively slowly varying T^3 dependence is dominant.[2] If the physical size were determined by the characteristics of sapphire, the value of the T^3 contribution could be reduced by more than 10^2. If the superconducting character of niobium were unchanged, a reduction in operating temperature to 0.9K would still show the rapid exponential reduction in sensitivity to thermal variations, resulting in an overall improvement of thermal sensitivity from $\sim 10^{-11}/K$ to $10^{-13}/K$.

We have measured the highest Q reported to date in a sapphire-filled superconducting cavity ($Q>10^9$) and present details in a following section. Such a resonator would additionally be lighter and stronger than a solid niobium cavity, giving a reduction in the shift due to gravity by 10 times. An additional advantage of the sapphire based resonator is that its large dielectric constant ($\varepsilon \sim 10$) allows operation at a lower, more convenient frequency ($\sim 3GHz$) with modest overall size (overall diameter < 7.5 cm).

1.4. Multiple Cavity Oscillator Design

We have chosen to study oscillator designs which, rather than separating the amplifier and resonator functions in separate elements, combine them by the use of multiple electromagnetic resonators. If the ruby could be included in the superconducting cavity itself, a single resonator would suffice, with the negative resistance due to the pumped ruby overcoming the positive resistance in the cavity, and inducing oscillation. However, the magnetic field required for ruby maser operation at microwave frequencies greatly reduces the cavity Q if allowed to penetrate the superconducting surface. The thin films we propose to use are even more sensitive than the bulk superconductor to such fields, and we propose a three-cavity design to isolate the superconducting cavity from the ruby cavity by a third coupling cavity. Most of the features of such a design are common to a two-cavity design, which was used in the present experiments, and we shall confine our present discussion to that case.

The essential electromagnetic features of a coupled two-cavity resonant system designed for this purpose are a high-Q stabilizing cavity, a low-Q cavity containing pumped ruby, and a coupling between the cavities. Such a two-cavity system will always have at least two modes, with the frequency difference between the modes depending on the isolated cavity frequencies f_1 and f_2, and on the coupling strength $\mathbf{k}$ in a particularly simple manner if the frequencies are defined and measured in the presence of the coupling holes, and not their absence.[5] Eigenfrequencies of the coupled cavities f_α and f_β can then be shown to be related by:

$$f_\beta - f_\alpha = \sqrt{(f_2 - f_1)^2 + (\frac{k}{4}(f_2 + f_1))^2} \tag{3}$$

and

$$f_\beta + f_\alpha = f_1 + f_2 \tag{4}$$

in the limit that $k \ll 1$ and $f_2 - f_1 \ll f_2 + f_1$. That is to say, if the coupling strength and the difference between the frequencies of the two isolated modes are both small enough, the splitting of the coupled modes is given by adding these two effects in quadrature.

The energy division between the two parts of the coupled system also has a particularly simple form in this case. If E_1 and E_2 are the energies in physical resonators one and two, energy ratios for modes α and β are given by:

$$\left[\frac{E_1}{E_2}\right]_\alpha = \frac{f_\alpha - f_2}{f_\alpha - f_1} = \left[\frac{E_2}{E_1}\right]_\beta = \frac{f_\beta - f_1}{f_\beta - f_2} \tag{5}$$

The energy involved in the coupling is given by

$$E_c = \mathbf{k}\sqrt{E_1 E_2} \tag{6}$$

and is assumed to be small.

In this simplified framework, the Q's of modes α and β can be written:

$$Q_\alpha^{-1} = \frac{E_{1\alpha}Q_1^{-1} + E_{2\alpha}Q_2^{-1}}{E_{1\alpha} + E_{2\alpha}} \tag{7}$$

and

$$Q_\beta^{-1} = \frac{E_{1\beta}Q_1^{-1} + E_{2\beta}Q_2^{-1}}{E_{1\beta} + E_{2\beta}} \tag{8}$$

where $E_{1\alpha}$ is the energy in resonator 1 for mode α, etc.

Oscillator design is relatively easy within this framework. The negative resistance associated with the pumped ruby is strongly frequency dependent, and is effective over a range of only a percent or so. Frequencies f_α and f_β must be chosen to be farther apart than this width to allow selection of the desired mode. If cavity 1 contains the ruby with mode α the coupled mode nearest in frequency to that of the isolated cavity 1, stabilized operation would result by tuning the frequency of the ruby resonance instead to that of mode β where nearly all of the energy is in cavity 2. Thus, the magnetic field is adjusted to give a strongly negative Q_1 at frequency f_β while showing a net positive Q_1 at f_α, as well as at f_1 the natural frequency of cavity 1. The oscillation condition can then be imposed by setting $Q_\beta^{-1} = 0$ in equation (8), from which can be calculated the maximum energy ratio which allows oscillation to occur in mode β. Frequencies and couplings can then be calculated from equations (3), (4), and (5).

This approach can be generalized to cover the case of three coupled resonators. The advantage over other methods is that actual mode and coupling configurations do not enter the calculations, rather, frequencies, energies and Q's, all easily accessable by experimental measurement, are used.

2. A Low-Q Experiment

Contributions to the frequency error in a high-Q oscillator fall into two categories; those due to variations in the natural frequency of the stabilizing cavity, and those due to deviations in frequency within the bandwidth of the cavity caused by factors other than the cavity itself. These latter frequency pulling effects scale inversely as the Q of the resonator, and thus can be studied effectively by deliberately building an oscillator with a poor Q. Effects that can be studied in this way include those due to output VSWR and a whole host of effects due to the ruby itself. These include thermal (white) noise, possible 1/f noise, possible amplitude and frequency pulling effects related to the pump signal, and the previously discussed pulling with magnetic field. All of these aspects can be fully characterized by reference to a source with very modest stability, if the Q can be reduced by, for example, a value as large as 10^7. That is, measurement of a stability of 10^{-10} with a Q of 100 would allow direct extrapolation of all these effects to a stability of 10^{-17} at a Q of 10^9.

Of particular interest and concern in this regard was the possibility of 1/f type modulation noise in the ruby, since no experiments have been previously conducted that place significant limits on such noise. The existence of such noise would place a Q-dependent limit to the stability allowed by the oscillator, and might indicate that a very high Q (10^{10} or above) was necessary, ruling out the use of a sapphire resonator.

To this end we modified an experimental setup designed primarily to measure the more conventional aspects of the ruby response to allow the first measurements of frequency stability in a ruby maser oscillator, and further, added a coupled (low Q) superconducting cavity to study the performance of the coupled cavity system, as well as the Q dependence of frequency pulling effects.

The various aspects of the oscillator were treated with differing degrees of care. The superconducting magnet was carefully constructed as a first attempt at what might be used in the final system. The ruby itself has been previously used in amplifier service, and can be expected to be a good example of what is available. The signal coupling line, however, was not constructed with an eye for stable VSWR, being instead designed to allow a wide range of coupling strengths. Similarly, the pump source had poor amplitude and frequency stability. Due to these reasons we do not feel that these preliminary results represent the best that can be obtained with this technique.

3. Measurements

The SCSMO components have been studied separately to establish the feasibility of the design. To achieve the part in 10^{17} stability level, our performance analysis has shown that the resonator cavity must have a quality factor Q of at least 10^9. Electromagnetic losses in the cavity can come from the dielectric material, from the superconducting material or from the interface region between the two. Results of measurements on all three effects will be presented and their implications for the Q of the cavity will be discussed.

The other principal component of the oscillator is the active element, the ruby maser. To determine the maser's suitability for the oscillator, a ruby maser oscillator stabilized with a copper cavity of modest Q was fabricated. The relatively low Q of the stabilizing cavity allows easy measurement of effects such as frequency pulling by the magnetic field and frequency pulling by the amplitude and frequency of the RF pump signal. Results of some of these measurements and some preliminary stability data for this system will be presented below.

3.1. Description of the Two-Cavity Maser Oscillator

Figure 1 shows the configuration that is being used to study the ruby maser oscillator. A size scale can be obtained by noting that the cylindrical ruby crystal (3) is 1.00 cm in diameter and is 1.15 cm tall. Both the cavity (5) containing the ruby and the cavity (8) stabilizing the oscillator are of the coaxial type; the center posts (4) and (7) and the coupling apertures (6) have been adjusted in size to give the operating frequencies and the disposition of energy between the two cavities deemed best for oscillator performance.

The outer wall (2) of the oscillator probe serves both as a waveguide for the ~13GHz pump signal applied to the ruby, and as the outer conductor of a coax for the ~2.7GHz oscillator signal. The inner conductor (1) of this coax is adjustable at the top of the probe to allow the coupling to the oscillation signal to be varied.

The magnet (9) is a superconducting solenoid with a persistent current switch. Compensating coils at the ends of the solenoid make it an "outside notch" magnet[6], producing a field constant to sixth order that is uniform to one part in 10^3 over a sphere of 2.54 cm diameter at the solenoid's center.

The pump signal is supplied by a Hewlett-Packard 8690A sweep oscillator. After amplication the oscillator signal is mixed in an HP 934A harmonic mixer with a signal from an Ailtech 360D11 frequency synthesizer. The low frequency output is further amplified and then is continuously sampled both by a HP 5245M counter and by a PDP 11/34 computer. A chart recording of the counter output provides a quick check of the oscillator's stability and drift, while statistical stability analysis is carried out on the computer system.

By measuring the lowest resonant frequencies of each cavity alone and of the two coupled modes, the energy splitting between the cavities in each coupled mode and the coupling strength can be determined. For the data reported below, the coupling strength was 2.5%. The stabilized mode had 85% of the energy in the stabilizing cavity and 15% in the ruby-filled cavity, while the other mode had the opposite ratio.

For magnetic fields applied at right angles to the ruby crystal's optic axis (the crystalline c-axis), there are two values of the magnetic field magnitude that will give ~2.7GHz splitting between chromium ion energy levels: ~.05T and ~.27T. For both of these cases the lowest frequency pump signal is ~13GHz. The data reported below were all measured with the ruby in the low-field mode near .05T.

3.2. Results of Frequency Stability Measurements

The cavity stabilized ruby maser oscillator described above has operated once successfully, and then only in a somewhat modified form, so the data reported here must be considered of a rather preliminary nature. Even with these reservations, some valuable conclusions and insights can be obtained from the data, so the results are being reported here.

When the oscillator was first cooled to 4.2K in the configuration described in the preceding section, the mode with most of the energy in the stabilizing cavity could not be driven into oscillation. To enable this mode to be studied, the portions drawn with heavy lines in Fig. 1 were plated with superconductor. With this lower loss condition, the stabilized mode was observed to oscillate at ~2.71GHz when cooled to 4.2K and lower temperatures. The upper (ruby- filled) cavity had its outer wall not plated with superconductor, so the mode at ~2.87GHz with most of the energy in the upper cavity displayed lower Q than the stabilized mode. By measuring frequency pulling effects and frequency stabilities for both modes at various temperatures, data for modes having a range of Q values could be obtained.

Fig. 2 shows examples of Allan variances of $\Delta f / f$ calculated from data obtained from several rather quiet periods of the oscillator's operation. The upper portion shows some of the best data obtained for the high-Q (Q = 70,000) stabilized mode at low temperature, and shows what our drift- removing algorithm does to the data curves. The lower portion of Fig. 2 shows curves for data obtained under various conditions. Note that cooling the ruby to 2.2K and improving the cavity Q from 25,000 to 70,000 do not yield improvement in the lowest observed σ values. We conclude that the limiting stabilities observed are not characteristic of the ruby maser, but rather are caused by some other device in the measuring system; a good candidate is the quartz crystal stabilized Ailtech frequency synthesizer being used as a local oscillator to beat down the oscillation frequency to audio frequencies.

The HP 8690A sweep oscillator used as a pump source was found to have great effect on the measured values of frequency and on frequency stability. The best data were obtained by carefully tuning this pump source to minimize the frequency pulling effects. A quieter klystron pump signal source has been obtained for comparison purposes for future measurements.

The output power of the oscillator is shown in Fig. 3 for a range of applied pump power, with the magnetic field tuned to optimum. Zero attenuation of the pump signal corresponds to ~100 milliwatts of pump power. The maximum output power in the region of saturation is 0.5×10^{-7} watt, a level well within our expectation and readily usable in our final design. Hence, the ruby volume will not need to be changed substantially in the final configuration of the oscillator.

The change of oscillator frequency with change in magnetic field was measured rather carefully, with results in agreement with our analysis. For the unstabilized mode with Q = 5,000, the fractional frequency pulling was found to be $\Delta f/f = 2.5\times10^{-8}\,\Delta H/H$, and this value varied as Q^{-1} for the other oscillation conditions measured. This value implies that, in order to achieve 10^{-17} stability with a cavity Q of 10^{9}, the magnetic field must not have a fractional variation larger than 10^{-9} over the measuring time τ. This field stability is tractable for a superconducting magnet operating in persistent mode, and having superconducting shields to attenuate ambient field variations.

Two frequency pulling effects are observed relating to signal amplitudes in the cavity: response to pump power changes, and response to oscillation amplitude changes. In the unstabilized mode with Q = 5,000, the two effects are nearly equal in magnitude at $\Delta f/f = \sim 3\times10^{-8}$ for a 3 dB power change. The response to changes in pump power is independent of the tuning of the magnetic field and varies as Q^{-1}. The response to changes in oscillation amplitude varies with magnetic field tuning, being positive if the field is tuned high and negative if the field is tuned low; the magnitude of this pulling does not decrease as fast as Q^{-1} when the Q increases. This output amplitude effect may result from magnetic field inhomogeneity at the ruby caused by the superconductors near the crystal. A test is planned with no superconductor on the oscillator probe to examine this possibility.

3.3. Measurements of the Cavity Losses

To obtain the cavity Q of 10^{8} required by the design, various sapphire materials have been examined for their electromagnetic losses at frequencies near 2.7GHz and at temperatures below 4.2K. Samples with losses below 10^{-8} have previously been described[7,8]. Recently a new sample has been obtained[9] with significantly lower losses, the loss tangent reaching $\delta = 7.0\times10^{-10}$ at the temperature of 1.5K. A description of the manufacturing process for this sample and of the loss measurements will be published elsewhere[10].

In measuring the sapphire losses, the samples are placed inside a lead- coated copper cavity and the decay time of the cavity-sapphire system is measured. Since initially lead will also be used to coat the sapphire substrate in forming the stabilizing cavity, the very low loss values reported above are sufficient evidence that losses in the superconducting film will not prevent the cavity from achieving a Q of 10^{8}. However, because the electromagnetic field is to be contained inside the cavity, the interface region between the lead film and the sapphire will also be exposed to the signal and could degrade the cavity Q. A measurement was made on a spherical sapphire substrate coated with a lead film to test this loss mechanism. The uncoated sapphire sphere displayed a loss value of $\delta = 1.17\times10^{-8}$,while the lead-coated sphere's loss was $\delta = 1.15\times10^{-8}$, both values measured at 1.5K. These results show that the losses in the interface region do not contribute appreciably to the total loss measured at this region near $Q = 10^8$.

Actually, these measurements have indicated the possibility of achieving even higher Q-values in the stabilizing cavity. Both the sapphire loss tangent measurements and the measurements in the spherical cavity have demonstrated that a Q of 10^9 is feasible for this cavity. A ruby maser oscillator stabilized with a cavity having a Q of 10^9 would be expected to have stability approaching $\Delta f / f = 10^{-17}$ for some range of sampling times.

4. Conclusions

Analysis of an application of the ruby maser to a Superconducting Cavity Stabilized Oscillator (SCSO) shows many attractive features. These derive from the mechanical stability inherent in an all-cryogenic design and from the properties of the ruby maser itself. A multiple-cavity design has been developed to allow physical separation of the high-Q superconducting cavity and the ruby element with its required applied magnetic field. Mode selection is accomplished in this design by tuning the ruby by means of the applied field. We conclude that such an oscillator would perform well, even with cavity Q's as low as 10^8, allowing the use of a superconductor-on-sapphire resonator with its greater rigidity and lower thermal expansion.

A first test of the Superconducting Cavity Stabilized Maser Oscillator (SCSMO) confirms the efficacy of the multiple-cavity design and the applicability of the ruby maser. Frequency variation less than 4×10^{-11} was measured in the stabilized mode and is attributed to the reference oscillator and to instabilities in the pump source. Variation of 10^{-10} was observed in the low-Q unstabilized mode, again attributable to pump fluctuations. Even so, direct scaling to a Q of 10^9 predicts a stability better than 10^{-15}. Together with results showing the lowest losses to date in sapphire at microwave frequencies, and preliminary experiments on superconductor-on-sapphire resonators, frequency stability levels as low as 10^{-17} are indicated.

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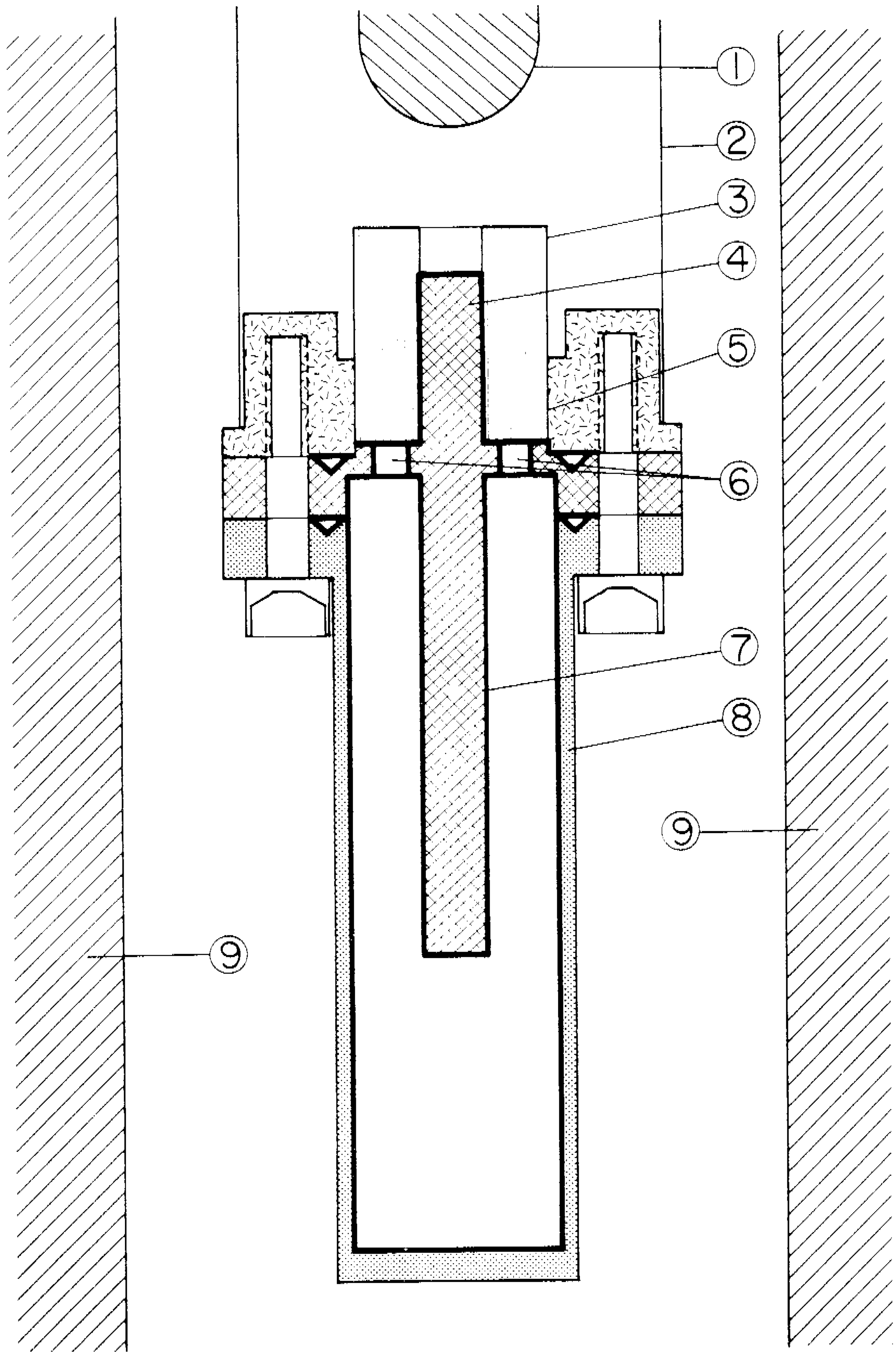

Fig. 1 RUBY MASER OSCILLATOR CONFIGURATION

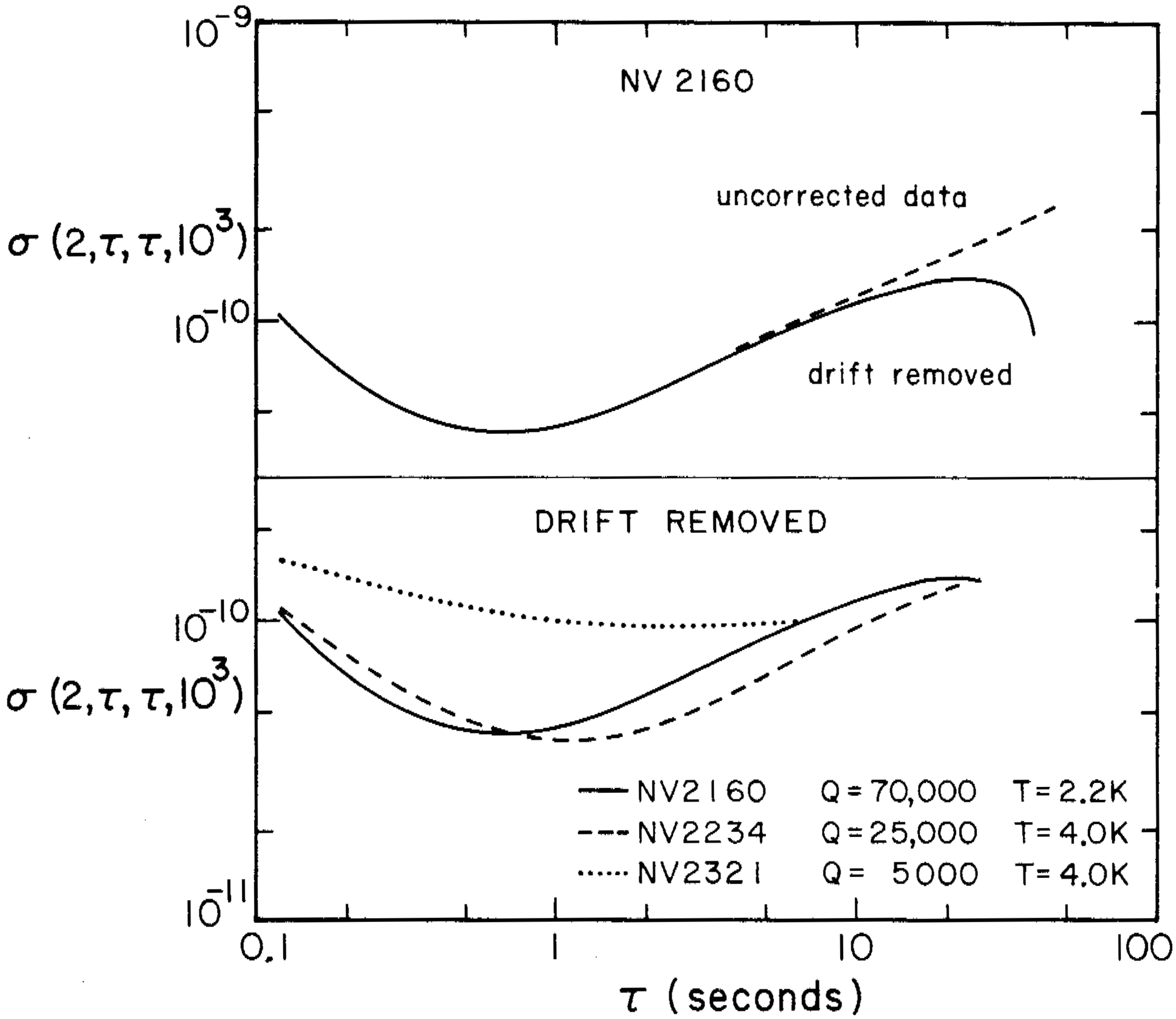

Fig.2 STABILITY DATA FOR THE RUBY MASER OSCILLATOR

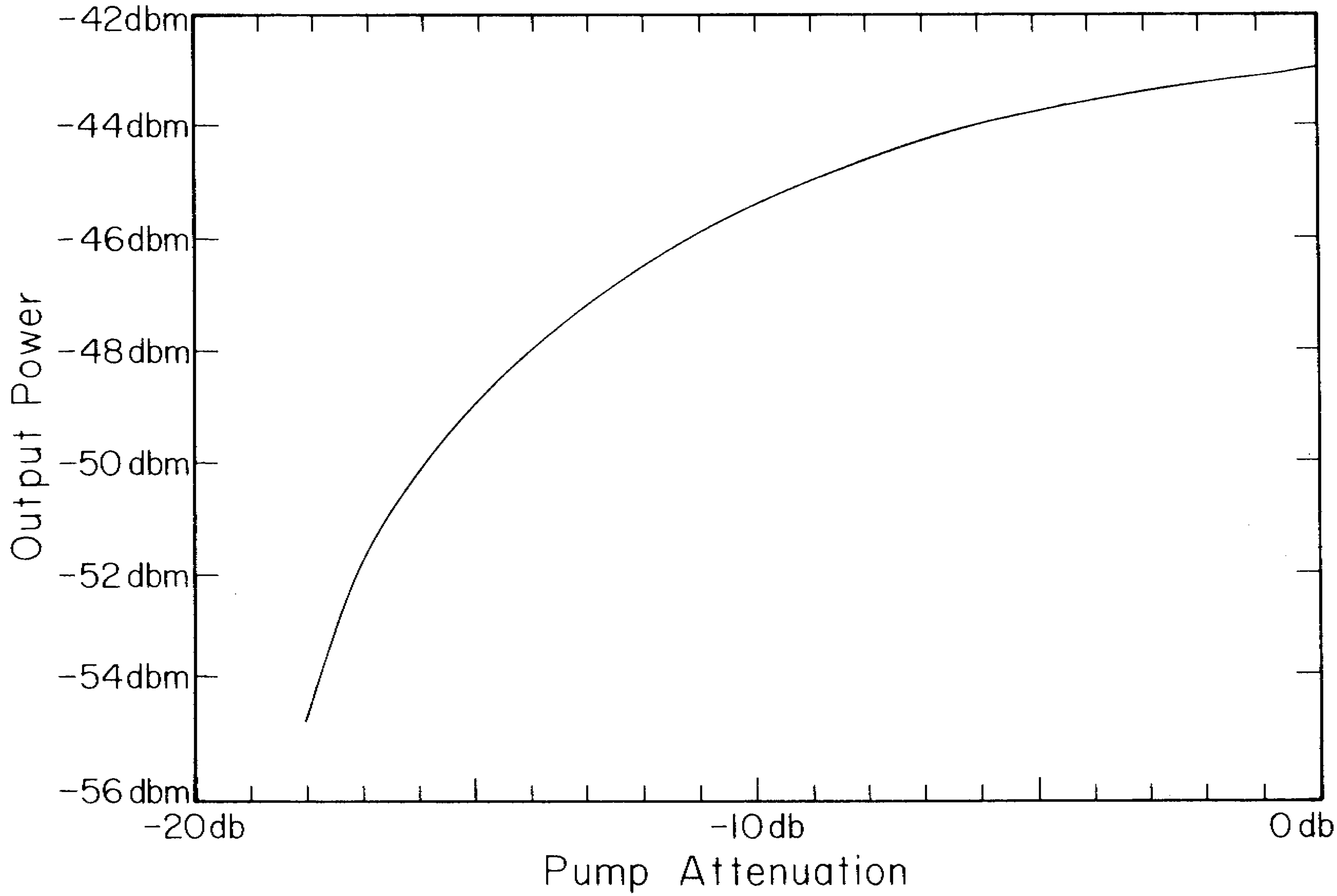

Fig. 3 RUBY MASER OSCILLATOR OUTPUT POWER vs. PUMP ATTENUATOR SETTING

QUESTIONS AND ANSWERS

MR. VESSOT:

The saphire losses have become an interesting theoretical problem, as in the paper by Brojinski and Panoff on the loss in ionic crystals. I was talking to Bob Clause and he told me to bring this up. His mode of oscillation is that of a whispering gallery, that only internal reflections are used and does not depend on superconducting surfaces at all.

DR. STRAYER:

That's intriguing.

MR. VESSOT:

It really is and I just wanted to bring this up. Perhaps you should tell about it.

DR. STRAYER:

He's wanted to set up a racetrack type resonator of uncoated saphire that will have very high Q, because the electromagnetic waves do not radiate out. The impedance missmatch at the boundary being enough to keep them in, and use that as a stabilizing element. That should work at room temperature. There is improvement in the Q as you cool it, but one possibility is using at room temperature as a stabilizing element. That should work at room temperature. There is improvement in the Q as you cool it, but one possibility is using at room temperature as a stabilizing element.

PROF. ALLEY:

Is it possible to use other than a Ruby maser amplifier, at some sacrifice, its the low noise of the ruby I gather that prompted you to do this. Could you couple in some more conventional high frequency frequency amplifiers?

DR. STRAYER:

We started to think about a galluim-arsenide FET amplifier operated at low temperatures, they have a high noise. One 1/f noise does not improve on cooling from the information I can gather. There are other solid state devices to be considered. The one on the horizon is HEMT which supposedly has low 1/f noise.

MR. REINHARDT:

On that doughnut type, what do you expect on something like that at room temperature?

DR. STRAYER:

I can't remember the exact values. I'm sorry.