APPLICATION OF SUPERCONDUCTIVITY TO PRECISION OSCILLATORS

S. R. Stein

Time and Frequency Division
National Bureau of Standards
Boulder, Colorado 80302

Introduction

One of the properties which is generally associated with precision frequency sources is a very high Q resonator. For example quartz crystals, cesium, and hydrogen have line Q's that range from about 10^7 to 10^9. Superconducting resonators began to appear attractive as components of high stability oscillator systems within the last two decades. Through 1960 the highest Q that had been reported for a superconducting resonator was 5×10^6.[1] Since that time, research at several laboratories has resulted in the production of superconducting microwave cavities with Q's as high as 1×10^{11}.[2]

Any technique which is appropriate for the construction of an ordinary oscillator can be adapted for use with superconducting cavities. Some of the techniques which have been used are (1) coupling a negative conductance device to the resonator, (2) placing the resonator in the feedback loop around a unilateral amplifier, (3) cavity stabilization by direct coupling of an oscillator to the resonator, (4) stabilization by placing the resonator in an FM discriminator and feeding back to a tuning element, and (5) filtering by a resonator which is isolated from the oscillator. This paper will present an overview of these methods. The fundamental problems and limitations common to all techniques (which are associated with the superconducting resonator and its cryogenic environment) will be identified. The various techniques will then be compared from the point of view of any additional limitations they impose on the frequency stability of the source with particular emphasis on short-term stability.

In addition to advances in superconducting technology in the last few years there has been a proliferation of solid state devices which operate at ever higher microwave frequencies and also at very low temperatures. It is therefore necessary to frequently reappraise the techniques available for realizing the ultimate stability of the superconducting microwave resonator. One of the most promising techniques is a negative resistance oscillator whose gain element is a parametric device. Since the gain is produced by a reactive device at a temperature of about 1K, it is possible to achieve noise temperatures as low as 20K.[3] At the same time, output powers in excess of 100mW at 9 GHz are feasible.[4] Such an oscillator is expected to be capable of improving the state-of-the-art in spectral purity and will have immediate impact on high precision frequency multiplication and synthesis in the infra-red.

Superconducting Microwave Resonators

The response of a normal metal at room temperature to microwave electromagnetic fields is adequately described by Ohm's law. When the metal is cooled, the conductivity increases as a result of the increase in mean free path. One is prevented, however, from achieving a very high Q by the anomalous skin effect which occurs when the mean free path becomes comparable to the skin depth. The behavior of a superconductor is quite different. At microwave frequencies the resistance of an ideal superconductor decreases exponentially as the temperature is reduced below the superconducting transition temperature. In real resonators this behavior does not extend to zero temperature. Instead, a loss mechanism which is independent of temperature is always observed. The result is that the Q of the resonator becomes constant, or residual, below some temperature. Figure 1 illustrates this behavior in the case of a niobium resonator in the TM_{010} mode at 8.4GHz.[5] The intersection of a horizontal line corresponding to a residual Q with the theoretical curve determines the highest temperature at which that resonator may be operated with a Q greater than or equal to the desired value.

Microwave resonators in a variety of modes are suitable for use in stable oscillators. However, there are design criteria which are specific to superconducting cavities. Because of the very low losses in the walls of the resonator, minor imperfections such as assembly joints or small amounts of foreign substance such as a surface oxide layer can seriously degrade the Q. Assembly joints may be located where there is no rf current in the desired mode. In the case of niobium, current-carrying joints may be fabricated by electron-beam welding.

Niobium and lead are the two superconductors which have shown the most promise for use in precision oscillators. These two materials are available commercially in sufficient purity, and techniques have been developed which permit complex resonator shapes to be fabricated from either material with surfaces which are clean, microscopically smooth, and relatively unstrained. The transition temperature of superconducting niobium is 9.25K while that of lead is 7.19K which means that a required Q can be achieved at a higher temperature than for most other materials. There are known superconductors with higher transition temperatures than niobium. They are, in general, brittle and difficult to fabricate into the necessary shapes. Furthermore, it has not yet been shown that one can prepare them with a sufficiently perfect surface for low residual losses.

For the best frequency stability niobium is the preferred material. Niobium resonators have exhibited the lowest residual surface losses and are unsurpassed in terms of mechanical stability and surface cleanliness. Two methods have been developed to manufacture the resonator from the bulk metal. In the first process, developed at Stanford University, a cylindrical resonator is machined in two pieces as shown in Fig. 2. The cavity is assembled by electron-beam welding and then alternately fired in ultra-high vacuum at about 1900°C and chemically polished.[6] More recently a technique has been developed which does not require ultra-high vacuum firing: The surface is prepared by electropolishing followed by anodizing.[7] This process potentially makes high quality niobium cavities available to many more laboratories; however, there is some evidence that the anodized surface degrades in time[8], and this is a possible disadvantage for oscillator applications.

Lead is an excellent material if the Q needn't be as high as achieved with niobium. If the cavity mode is restricted so there is no normal electric field at the walls, Q's in excess of 10^{10} may be achieved.[8] The primary advantage of lead is that high quality surfaces can be made in almost any laboratory using standard electroplating techniques. Unlike niobium, high quality lead surfaces have not been successfully produced when the resonator has been machined from the bulk material.

Oscillator Performance

For the purpose of this discussion, the frequency fluctuations of any oscillator based on a superconducting resonator can be separated into two categories: Statistical fluctuations around the center of the resonance and perturbations of the resonance frequency itself. The second category determines the ultimate performance level for any oscillator which is relatively independent of its design. It includes temperature, power level, and mechanically induced frequency shifts.

Since most superconducting oscillator research has been performed with solid niobium cavities and the best results have been obtained with these cavities, this discussion of performance will relate most directly to solid niobium resonators fabricated by the Stanford technique.

Two independent effects transduce a temperature change of the microwave resonator into a shift of its resonant frequency. Thermal expansion or contraction changes both the mechanical and the electrical length of the resonator while the variation in the penetration of the rf magnetic fields with temperature changes the effective electrical length. The penetration depth varies exponentially with temperature and is the dominant effect above 1K. Figure 3 shows the total frequency shift with temperature.[9] The coefficient of the fractional frequency is 6×10^{-9}/K at 1.75K and 4×10^{-10}/K at 1.3K.[10] Inside of a vacuum can contained within a dewar it is possible to do excellent temperature regulation. With a single stage regulator drift rates of 10^{-5}K/week have been observed while the fluctuations from second to second were too small to be observed.[11] The ease of temperature regulation in a cryogenic environment helps to compensate for some of the added complexity.

Any oscillator system will operate with some energy stored in the resonator. Because of the radiation pressure of these fields and the dependence of the surface reactance on the rf field level, there is necessarily a static frequency shift of the superconducting resonator. Some measurements indicate that the frequency offset is proportional to the stored energy. Figure 4 shows this type of behavior at high field levels.[6] The total fractional frequency shift observed in one experiment for 10^{-7} J of stored energy was 10^{-11}.[11] The total frequency offset determines the size of the frequency fluctuations which result from oscillator power fluctuations. Frequency fluctuations from this source can be reduced by decreasing the operating power level but only if a lower signal-to-noise ratio can be tolerated, otherwise power regulation is necessary.

The third major perturbation of the superconducting cavity resonant frequency results from mechanical strains. For a TM_{010} mode cavity resonant at 8.6 GHz the static stress due to the force of gravity produces a fractional frequency shift of 1×10^{-9} from the zero strain value.[10] Consequently, changes in either the acceleration of gravity or the orientation of the superconducting cavity result in frequency shifts of the resonance. For a TM_{010} mode resonator maintained in a fixed location the variations in gravity are not significant, but the angular coefficient is 1×10^{-14}per arc second.[11] This sensitivity permits many factors to be transduced into short-term, diurnal, and long-term frequency shifts of the resonator. Another possible effect of the stress of gravity on the resonator is creep of the niobium. The creep process is not well understood at these temperatures and has not been measured.

Elastic deformation of the resonator due to mechanical vibrations produces significant fluctuations in the center frequency. Studies of the most rigid solid niobium cavities have shown the frequency stability in an oscillator system to be limited by vibrations for averaging times between 10ms to 10s.[11] Some vibrations are coupled to the resonator from the laboratory but the most significant vibrations which have been observed were due to boiling cryogen used to maintain the low temperature in the dewar.[12]

Oscillator Systems Employing Superconducting Cavities

If the center of the resonance is sufficiently constant, then other sources of noise will determine the ultimate stability of the superconducting oscillator system. The frequency fluctuations about the center of the resonance are highly dependent on the design of the particular oscillator, however a lower limit corresponding to the case where all noise sources are filtered by the resonator can be determined. If the perturbing noise is white, then the phase of the oscillator does a random walk.[13,14,15] The one-sided spectral density of the phase fluctuations, in a form appropriate for microwave resonators, is given by

$$S_\phi(f) = \left(\frac{\nu_0}{f}\right)^2 \frac{kT}{2P_a\, Q_E\, Q_L} \qquad (1)$$

where ν_0 is the operating frequency, k is the Boltzman constant, T is the absolute temperature, P_a is the power dissipated in the load, and Q_E and Q_L are the external and loaded Q's respectively. In the case of a superconducting cavity with $Q_E = 10^{10}$, $Q_L = 5 \times 10^9$, $P_a = 10^{-3}$W, $\nu_0 = 9.2 \times 10^9$Hz, and $T = 1$K,

$$S_\phi(f) = 10^{-20}\ \text{Hz}/f^2.$$

The active element in a practical oscillator will dominate the thermal noise. In this case T must be interpreted as the effective noise temperature of the device. Such noise temperatures vary from approximately 20K for varactor parametric amplifiers to more than 10^4K for a transferred-electron device.

Another important limitation on the stability of a superconducting oscillator is additive noise which results from a white noise voltage generator at the output of the oscillator. In an ideal oscillator the additive noise is due to output buffer amplifiers or a user device. The spectral density of the phase fluctuation is

$$S_\phi(f) = kT'/2P_a \qquad (2)$$

where T' is the effective noise temperature of the circuitry which sees the output of the oscillator.[13] If the effective noise temperature is 300K and the available power is 10^{-3}W, then

$$S_\phi(f) = 2 \times 10^{-18}/\text{Hz}.$$

In this case the additive noise dominates the oscillator spectrum for Fourier frequencies greater than .07 Hz. Under the same conditions the rms fractional frequency fluctuations are given by

$$\sigma_y(\tau) = \left[\left(\frac{8.3 \times 10^{-21}}{\tau^{\frac{1}{2}}}\right)^2 + \left(\frac{4.3 \times 10^{-20} f_h}{\tau}\right)^2\right]^{\frac{1}{2}}$$

where f_h is the noise bandwidth of the measurement system.

Equations (1) and (2) show that both the random walk of phase and the additive noise can be reduced by increasing the available power, however, this technique is limited by several factors. The nonlinearity of the resonator couples amplitude and phase modulation and may ultimately limit the stability. If this is not a problem, then at some field level the resonator breaks down. Finally high power levels may exceed the dynamic range of the user device such as a mixer in a superheterodyne receiver.

Because of the tremendous stability potential of superconducting resonators a variety of techniques have been used to construct superconducting oscillators.[11, 16-18] The goals of this research have varied. Some oscillators have been constructed to illustrate feasibility, some to accomplish modest stability goals for further research on superconducting resonators, and others to achieve the ultimate frequency stability over some range of Fourier frequencies or averaging times. As a result, the achieved frequency stability for each technique is probably a poor indication of its capabilities. Instead of making such a comparison, this paper will outline some of the advantages or disadvantages of each method from the point of view of achieving the best possible short-term frequency stability.

The techniques discussed here use the superconducting resonator in three different ways - as the sole resonator of an oscillator circuit, as an auxiliary resonator to stabilize a free-running (noisy) oscillator, or as a filter which provides no feedback to the source.

Figure 5b illustrates how an oscillator may be realized using a superconducting resonator and a unilateral amplifier. Oscillation can occur when the amplifier gain exceeds the losses and the total phase shift around the loop is a multiple of 2π rad. Automatic gain control or limiting is necessary in order to produce oscillations at the desired power level. The resonator may be used in either transmission or reflection but the transmission mode is preferable because the insertion loss of the resonator suppresses spurious modes of oscillation which do not lie in its pass bands. This technique has received considerable attention because of its simplicity.[16,17] The only element which needs to be located in the dewar is the superconducting cavity which can be connected to the room temperature amplifier by long lengths of transmission lines. However, this virtue is its major detraction when state-of-the-art frequency stability is desired. Changes in the phase length of the transmission lines produce proportional frequency shifts. If $\Delta\phi$ is the phase change from any source, the fractional frequency shift is

$$\Delta f/f = \Delta\phi/2Q_L. \tag{3}$$

The phase changes due to such factors as thermal expansion and vibrations are sufficiently large in a cryogenic system that they totally dominate the short-term stability and drift of such an oscillator.

One solution to this problem is to use an amplifier which functions in the same low temperature environment as the resonator and is connected to it by short rigid transmission line. This is possible at microwave frequencies in the case of both tunnel diode amplifiers and varactor diode parametric amplifiers. Both of these devices function by generating a negative conductance at the resonator frequency. Since they are bilateral, they can simply be connected to the superconducting cavity through an impedance transforming network as shown in Fig. 5a. When the negative conductance of the amplifier exceeds the positive load conductance of the resonator oscillations result. Jimenez and Septier have demonstrated the feasibility of the tunnel diode superconducting oscillator at 3 GHz and McAshan has successfully operated a degenerate parametric superconducting oscillator.[18,19] The major advantage of the tunnel diode oscillator is that it requires only dc bias power for operation. On the other hand, there are several disadvantages. Shot noise in the tunnel junction limits currently available tunnel diode amplifiers to an effective noise temperature of 450K at 9GHz.[3] In addition, the very low operating voltage limits the theoretical output power to 1mW at 10GHz from commercially available devices (having peak current less than 20mA). If other problems were solved these two difficulties could limit the frequency stability of the tunnel diode superconducting oscillator. In contrast, cooled parametric amplifiers have demonstrated 20K noise temperatures and room temperature non-degenerate parametric oscillators have produced more than 100mW at 9GHz.[3,4]

The most widely studied and successful technique for realizing a superconducting oscillator has been the stabilization of a free-running oscillator with a superconducting resonator.[18] One technique for accomplishing this, called cavity stabilization, is shown in Fig. 5c. The oscillator is injection locked by the power which is reflected from the superconducting resonator. The stabilization factor, which is the ratio of the free-running oscillator frequency fluctuations to the cavity-stabilized oscillator frequency fluctuations, has been calculated by several authors.[21,22] In the high Q limit for the transmission stabilizer it is just the ratio of the Q of the superconducting cavity to the Q of the free-running oscillator. Equation 1 shows that the best possible performance reduces to that of an oscillator built with the superconducting cavity as its only resonator. There are two major disadvantages to this technique. First, room temperature oscillators such as klystrons and Gunn-effect devices have extremely high noise temperatures. And second, the frequency offset from the center of the resonance is proportional to the line length between the oscillator and the cavity just as in the loop oscillator.

Another technique is possible for stabilizing a voltage controlled oscillator. The superconducting resonator is the frequency sensitive element of a discriminator which generates an output voltage proportional to the frequency difference between the oscillator and the center of the superconducting cavity resonance.[23] Although this system also has a long path length between the room temperature oscillator and the superconducting cavity, it is possible to design the discriminator so that the dependence of the oscillator frequency on this path length is greatly reduced. This is accomplished by using phase modulation sidebands on the carrier frequency to provide the reference for locating the plane of the detuned short of the superconducting cavity. Despite the fact that this technique also uses a noisy room temperature oscillator its performance is not limited by this fact. This is true because in such a system it is possible to greatly multiply the phase vs. frequency slope of the resonator by using external amplifiers. In this way the frequency fluctuations of the free-running oscillator may be reduced until the performance level determined by the microwave detectors is reached.

Figure 5e, included for generality, shows a superconducting resonator being used to filter the output of a precision oscillator.[20] This application is particularly important when the oscillator is to be used as a source for frequency multiplication. For example, it has been shown that state-of-the-art quartz crystal oscillators may be multiplied to 0.5THz before the carrier is lost in the phase noise pedestal. However, if the same oscillator is filtered by a passive superconducting cavity with loaded $Q = 2 \times 10^9$ it could in principle be multiplied to 100THz.[24]

The conclusion of the above discussion is that two types of superconducting oscillators appear most promising for improved short-term-stability: stabilization of a VCO and the all cryogenic, negative resistance oscillator. The fundamental limitations of the two devices are similar so the most important differences at this time are the practical problems of implementation: The VCO stabilization system has all the critical elements outside the dewar where they are readily available for adjustment and experimentation, but they are necessarily sensitive to problems of temperature fluctuations and vibration. On the other hand, the negative resistance oscillator is compact and totally contained in the highly controlled cryogenic environment. It will, however, present some new technical difficulties such as heat dissipation and device parameter fluctuations.

Semiconductor Devices at Cryogenic Temperatures

The tunnel diode and parametric oscillators have been discussed with no mention of the behavior of semiconductor devices at cryogenic temperatures. This section briefly discusses the temperature dependence of the main semiconductor properties and how it affects device operation.[25]

The number of free carriers in an intrinsic semiconductor decreases exponentially with temperature as $\exp(-Eg/2kT)$ where Eg is the energy gap. At 4.2K, $kT = 3.6 \times 10^{-4}$ eV while the gap energy is approximately 1 volt so the intrinsic semiconductor behaves like an insulator. In most extrinsic semiconductors the ionization energy is still large compared to 2kT so that the free carriers tend to freeze out. This is one of the major limitations of Si and Ge devices at cryogenic temperatures. Another property which changes markedly with temperature is minority carrier lifetime. Majority carrier devices, such as JFETS, are therefore preferred at cryogenic temperatures while silicon or germanium bipolar transistors do not work at all at 4.2K Certain n-type semiconductors (GaAs,InAs,InSb) have extremely small ionization energy. Consequently they are not affected by carrier freeze out. Furthermore, in certain devices free carriers may be produced by means other than thermal excitation. For example, in the case of MOSFETS and true Zener diodes, carriers are produced by field effect and in the case of tunnel diodes the semiconductor is so heavily doped that carrier freeze-out does not occur and the tunneling of carriers through the thin barrier is essentially temperature independent.

Although many commercially available paramp varactor diodes and tunnel diodes have good electrical properties at cryogenic temperatures there is an additional problem due to heat dissipation. The thermal conductivity of the semiconductor material remains high but the conductivity of the case usually degrades seriously by 4.2K. At modest power levels the active part of the device can heat up sufficiently to degrade its noise performance and change its properties.

The Parametric Oscillator

At NBS work is in progress on a superconducting parametric oscillator. This project is motivated by the need for a microwave signal with high spectral purity for multiplication to the infrared. The goal is to be able to measure the frequency of an infrared laser by direct synthesis from X-band with no loss in precision as compared to the primary cesium standard. The spectral purity must be sufficiently good to eliminate the need for intermediate local oscillators in the multiplication chain.

At the present time the only device which has a demonstrated capability of single step multiplication from 10GHz to 4THz is the superconducting point contact.[26] The power required is approximately one milliwatt. The need for such high power levels is a strong factor favoring the varactor diode as the active oscillator element. Since the process of frequency multiplication of order n increases the power in the phase noise sidebands relative to the carrier by n^2, very stringent requirements are placed on the source spectrum. It is particularly important to reduce the level and width of noise pedestal in order to extend the highest frequency which can be reached by multiplication before the carrier disappears into the noise. For this reason, the output of the oscillator must be taken from an independent transmission probe. This provides maximum filtering by the resonator of all noise sources within the oscillator.

The equivalent circuit of the parametric oscillator is shown in Fig. 6. The design is an extension of the basic lower-sideband upconverter circuit.[27] Power from a pump oscillator at frequency Ω_3 is coupled into the varactor diode in order to produce the time varying capacitance $C_3\sin(\Omega_3 t + \phi_3)$. Two resonators whose frequencies are Ω_1 and Ω_2 are coupled together by the varying capacitance. The frequencies are related by $\Omega_1 + \Omega_2 = \Omega_3$. The two tanks have sufficiently high Q that they appear to be short circuited at frequencies other than their resonant frequencies. The net effect of pumping the varactor is that the admittance presented to each tank circuit at its resonant frequency is a negative real conductance. When the capacitance variation reaches a critical level the negative conductance of each circuit exceeds the load conductance and oscillation occurs.

After an abrupt rise, the output power increases linearly with pump power until a broad maximum is reached. Two operating modes appear possible. If the oscillator is operated at maximum output the power fluctuations in the resonator are much reduced compared to pump power fluctuations. The problem of amplitude to phase noise conversion in the oscillator is thereby reduced. The alternative is to operate in the linear region in which case the oscillator power level can be regulated by controlling the pump power.

A potential source of noise which is unique to parametric oscillators is frequency fluctuations in the pump source. In order to solve this problem only one of the two resonators in the oscillator circuit is superconducting. In this case Q_2 is much larger than the Q_1 and the pump frequency fluctuations divide between the two resonators inversely in proportion to their Q's.[28] Thus

$$\frac{\Delta\Omega_2}{\Omega_2} = \frac{Q_1}{Q_2}\left(1 + \frac{\Omega_2}{\Omega_1}\right)\frac{\Delta\Omega_3}{\Omega_3} \tag{4}$$

Recent Results and Conclusions

We have seen that superconducting oscillators have potential for very great precision. This capability results primarily from the very high attainable Q, the small nonlinearities, the high operating frequency, and the very stable cryogenic environment. However, in order to obtain good performance there are a number of practical problems which must be minimized. In particular it is necessary to control temperature fluctuations of the resonator, vibration of the walls of the resonator, and fluctuations in the operating power level.

The best performance of a superconducting oscillator to date has been obtained with a device constructed by the author and J. P. Turneaure at Stanford University. This oscillator employs the cavity stabilization system of Fig. 5d in which the frequency of a free-running VCO is controlled to equal the resonant frequency of a superconducting cavity.

Fig. 7 shows the measured time domain stability of a single superconducting oscillator. The rms fractional frequency fluctuations in a 10^4 Hz bandwidth decrease with averaging time approximately as 5×10^{-15} s/τ reaching a noise floor of 6×10^{-16} for times longer than 10s. Measurements in the frequency domain indicate that the random component of the phase fluctuations is white for Fourier frequencies between 10 Hz and 50 kHz: The spectral density of the phase fluctuations is $S_\phi(f) \approx 7 \times 10^{-13}$/Hz. For Fourier frequencies below 300 Hz there are several peaks in $S_\phi(f)$ due to coherent frequency modulation of the oscillator by mechanical vibrations. The largest of these bright lines have rms amplitudes of approximately 8×10^{-5} rad which is consistent with the stability observed in the time domain. The long-term behavior of the superconducting oscillator was measured via a comparison with an ensemble of cesium frequency standards. The result of a fit to a model including linear drift was a frequency drift rate of 1×10^{-14}/day for the best superconducting oscillator system.[29]

Although this performance is excellent, there are several applications such as frequency multiplication and long baseline interferometry which need even better long-term or short-term frequency stability. Since factors which now limit superconducting oscillators do not appear to be fundamental in nature, further research should result in significant progress. The superconducting parametric oscillator provides an opportunity to minimize external perturbations, since all of its critical components are contained within the very stable cryogenic environment, thus making it possible to come closer to the frequency stability limits determined by thermal noise and the filtering action of the superconducting resonator.

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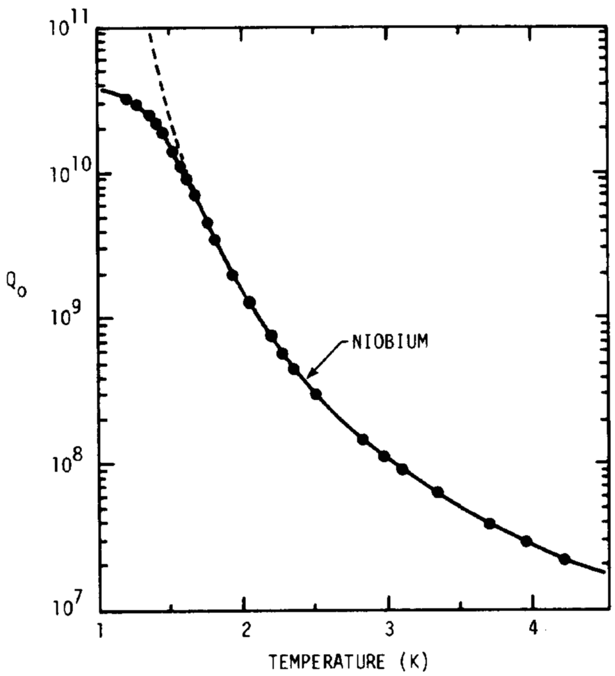

FIG.1 The Unloaded Q of an X-band TM_{010} mode niobium cavity.

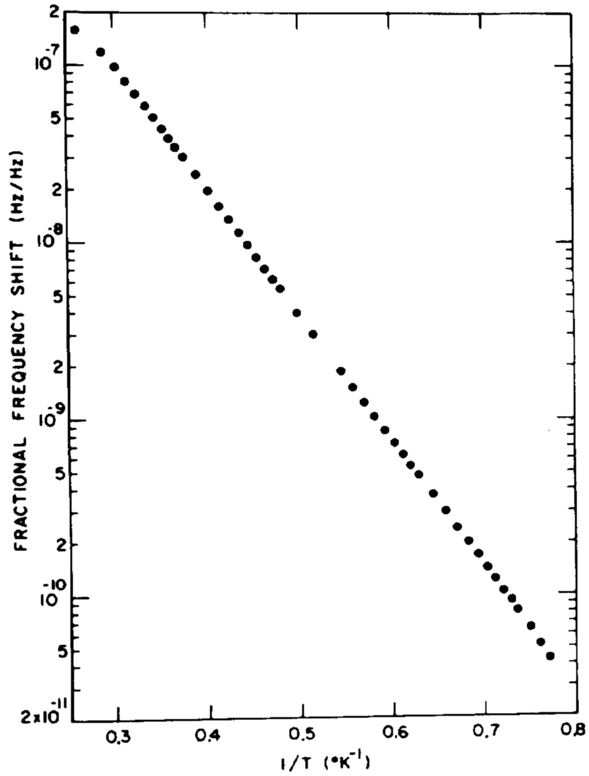

Fig.3 The temperature dependence of the fractional frequency of an X-band TM_{010} mode niobium cavity.

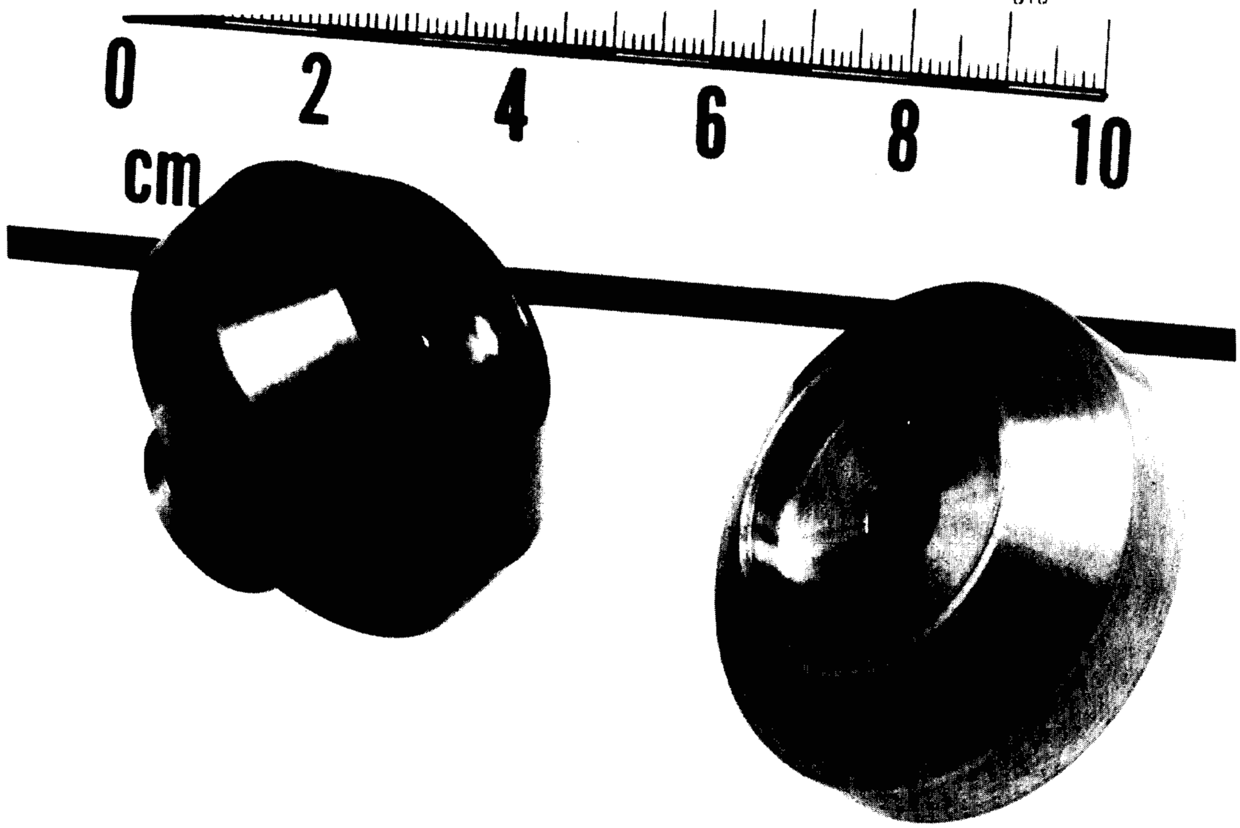

Figure 2. The two halves of an X-band TM_{010} mode niobium cavity before electron-beam welding.

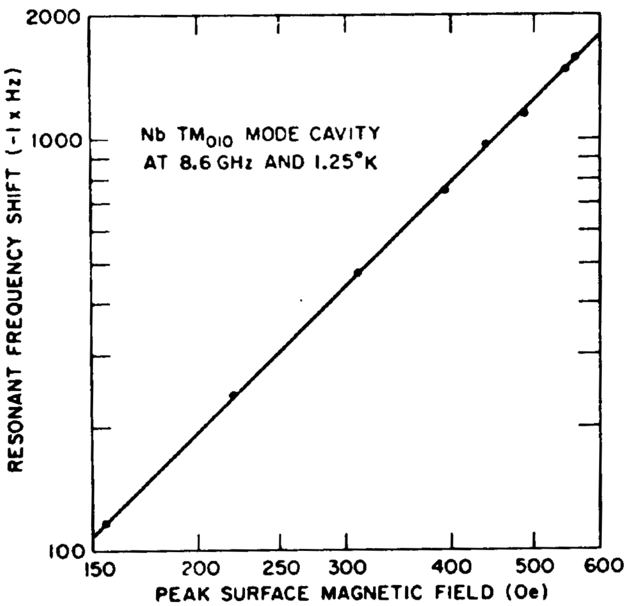

Fig.4 The magnetic field dependence of the resonant frequency of an X-band TM_{010} mode niobium cavity

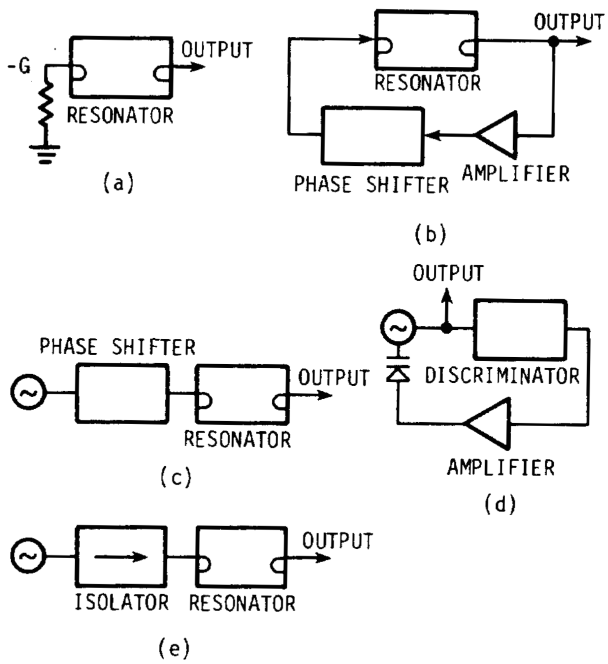

Fig.5 Block diagrams illustrating several superconducting frequency sources: (a) Negative resistance oscillator. (b) Loop oscillator, (c) Cavity stabilized oscillator, (d) stabilized voltage-controlled oscillator, and (e) passive filter.

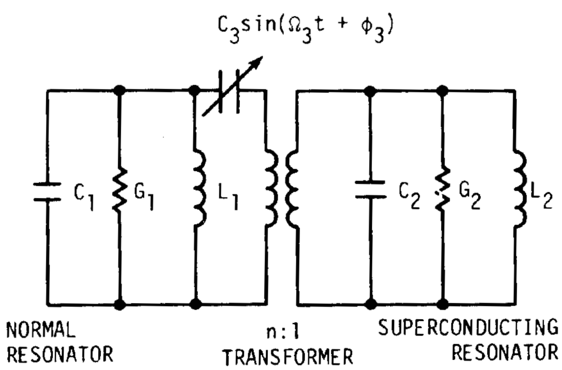

Fig.6 The equivalent circuit of a superconducting parametric oscillator.

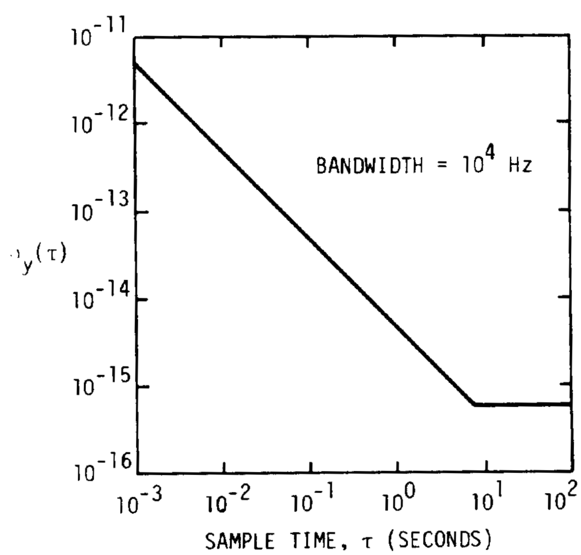

Fig.7 The fractional frequency fluctuations of a superconducting-cavity stabilized VCO.