This is the last in a seven part series on the potential applications of superconductivity in space. Superconducting oscillators have achieved better frequency stability than any other device for averaging times of 10 s to 1000 s. This high stability results from the use of solid niobium resonators having Q factors greater than 10^{10}. Such oscillators have direct applications as clocks and spectrally pure sources. They may also be used for accurate measurements of many physical quantities and to perform a variety of experiments on fundamental constants, relativity, and gravity waves.

Space applications of superconductivity: resonators for high stability oscillators and other applications

S.R. Stein

A resonant circuit has a strong response near a frequency, called the resonant frequency (ν_0), and a weak response for very different frequencies. Such circuits are needed in order to separate a desired ac signal from signals at other frequencies. The bandwidth ($\Delta\nu$) is a measure of the selectivity of the resonance. However, since most applications place requirements on the relative width of the resonance ($\Delta\nu/\nu_0$), the most commonly used figure of merit for a resonator is its quality factor or Q which is equal to $\nu_0/\Delta\nu$. The Q is defined as the ratio of the energy stored in the resonator to the energy dissipated during one radian of the oscillation. Thus high Q implies both great selectivity and small power loss.

The first electrical resonators consisted of coupled lumped reactances, the stored energy oscillating between the electric field of a capacitor and the magnetic field of an inductor. Resonator cavities were introduced by W.W. Hansen (1938). They usually consist of a volume of any shape almost completely enclosed by high conductivity walls and are necessary at high frequencies because of the difficulty of fabricating lumped circuit elements. Cavities have the advantage of reasonable dimensions and extremely high Q for the frequency range from 100 MHz to more than 10 GHz. The factor which limits the Q is the surface resistance of the metallic walls, there being no need to use dielectric materials. Since the conductivity of metals increases as the temperature is decreased, the Q can be improved by operation at cryogenic temperatures. The improvement obtained in this manner in normal metals is severely limited by the onset of the anomalous skin effect which halts the increase in conductivity when the electronic mean free path becomes larger than the skin depth. For usual microwave frequencies, the rf surface resistance of superconductors is small compared to what can be achieved with normal metals. It decreases exponentially as the temperature approaches absolute zero, until it is limited by non-intrinsic effects. At the present time, it is possible to obtain Q's in excess of 10^{11}, which is an improvement by a factor of about 10^7 compared to a room temperature copper resonator (Turneaure,[33] Turneaure[30], Kneisel[15], Diepers and Martin,[6].

The applications of superconducting cavities can be divided into two categories which stress different, but related properties of superconductivity. High power applications such as electron accelerators, proton and ion accelerators, particle accelerators and rf plasma confinement use superconductivity in order to achieve the low levels of power dissipation required for continuous operation. On the other hand, a variety of low-power applications make direct use of the extremely narrow linewidth. The cavities can be incorporated into high stability oscillators with unsurpassed performance, which can be used as flywheel oscillators in physics experiments directly involving clocks, or in large systems which require precise timing such as Doppler tracking, satellite navigation, and radio astronomy. The cavities can be used directly to filter noisy signals, to impedance match between devices having very large impedance differences, and to store energy from very weakly radiating devices. Superconducting cavities can also be used as transducers for a variety of physical quantities. They make very sensitive displacement detectors since the frequency changes in proportion to length. They have also been used to measure materials' properties in solid dielectrics, semiconductors and liquid helium, and to measure the thermal expansion of metals.

In addition to these applications there are also special uses which aren't easily categorized. Of course, superconducting cavities have been and will continue to be an important vehicle for the study of rf superconductivity. They can also be used in certain novel and unique ways such as in cesium frequency standards and electromagnetic gyroscopes.

Extensive general reviews of superconducting cavities have been written by Maxwell[17] and Pierce[21]. Shorter reviews of applications were written by Hartwig[8] and Turneaure[31]. This report will stress devices and instrumentation based on superconducting cavities and their applications. The reader may refer to the earlier reviews for more complete background information and to the paper by Barnes, et al.[1], for a description of the specification and measurement of frequency stability. Since superconducting cavities are common to all the devices and applications, and superconducting cavity oscillators are used in most of them, these topics will be discussed first, followed by discussions of specialized devices and applications.

The authors are at the Time and Frequency Division, National Bureau of Standards, Boulder, CO 80303, US. Work supported by NASA under contract number A–437018 (JM). Paper received 7 July 1978.

0011-2275/80/007363-09 $02.00

Superconducting cavities

Fabrication. 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 behaviour 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 behaviour 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. Fig. 1 illustrates this behaviour in the case of a niobium resonator in the TM_{010} mode at 8.4 GHz (Turneaure and Weissman,[34]). The intersection of a horizontal line corresponding to a residual Q value with the theoretical curve determine the highest temperature at which that resonator may be operated with a Q 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 high stability 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 niobium is 9.25 K, and that of lead is 7.19 K, which means that a required Q can be achieved at higher temperatures than for most other materials. Several laboratories are studying superconductors with higher transition temperatures than niobium, such as Nb_3Sn, but the results so far are not as good as for pure niobium.

For the best frequency stability, niobium is the preferred material. Niobium resonators have exhibited the lowest residual surface losses and are so far unsurpassed in terms of mechanical stability and surface cleanliness. Q's higher than 10^{11} have been achieved. Two methods have been developed to manufacture the resonator from the bulk metal. In the first process, a cylindrical resonator is machined in two pieces and assembled by electron-beam welding. It is then alternately fired in ultra-high vacuum at about 1900°C and chemically polished (Turneaure and Viet,[33]). More recently a technique has been developed which does not require ultra-high vacuum firing: the surface is prepared by electropolishing followed by anodizing (Diepers, Schmidt, Martens and Sum,[5]). 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 and this is a possible disadvantage for oscillator applications (Pierce,[21]).

Lead is an excellent material if the Q needn't be as high as achieved with niobium. If the cavity mode must be restricted so there is no normal electrical field at the walls, Q's in excess of 10^{10} may be achieved (Pierce,[20]). 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. It has recently been suggested that resonators be fabricated from a solid piece of dielectric such as sapphire by plating the outer surface with a superconductor; Q's as high as 10^8 (unpublished results of Braginskii) have been obtained by this method. It is possible that resonators made this way may be mechanically more stable than traditional designs, but no experimental evidence is available yet.

Oscillator Stability. 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 centre of the resonance and perturbations of the resonant frequency itself. The second category determines an 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 electron beam welding.

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 1 K. For a TM_{010} mode resonator the measured (Stein and Turneaure,[28]) coefficient of the

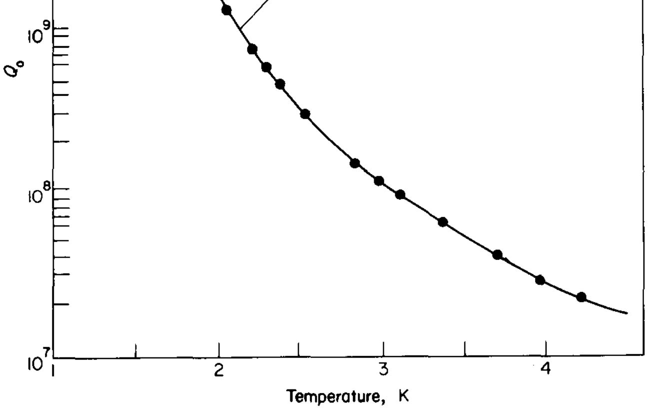

Fig. 1 The unloaded Q of an X-band TM_{010} mode niobium cavity[34]

fractional frequency is 6×10^{-9}/K at 1.75 K and 4×10^{-10}/K at 1.3 K. Inside 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, (Stein,[14]). The ease of temperature regulation in a cryogenic environment helps to compensate for some of the added complexity of cryogenic devices.

Any oscillator system operates 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. The total frequency shift observed in one experiment was $\Delta\nu/\nu = 10^{-11}$ for 10^{-7} J of stored energy (Stein,[24]). 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 resonant frequency of a superconducting cavity results from mechanical strains. For a T_{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 (Stein and Turneaure,[27]). 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 s (Stein,[24]). 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 centre-frequency. Studies of very rigid solid niobium cavities have shown the frequency stability in an oscillator system to be limited by vibrations for averaging times between 10 ms to 10 s. Some vibrations are coupled to the resonator from the laboratory, but the most significant vibrations which have been observed were due to boiling cryogen (liquid nitrogen) used to maintain the low temperature in the dewar.

If the centre frequency 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 centre 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. 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 (Stein,[25]). In the case of a superconducting cavity with $Q_E = 10^{10}$, $Q_L = 5 \times 10^9$, $P_a = 10^{-3}$ W, $\nu_0 = 10^{10}$ 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 20 K for varactor parametric amplifiers to more than 10^4 K for a transferred-electron device.

Another important limitation on the stability of a superconducting oscillator is additive noise resulting 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 fluctuations 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 (Stein,[25]). If the effective noise temperature is 300 K 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 0.07 Hz. Under the same conditions, the rms fractional frequency fluctuations are given by

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

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 super-heterodyne receiver.

Oscillator design. Because of the tremendous stability potential of superconducting resonators, a variety of techniques have been used to construct superconducting oscillators (see Fig. 2). 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 potential performance. Instead of making such a comparison, this chapter will outline some of the advantages or disadvantages of each method from the point of view of achieving the best possible frequency stability.

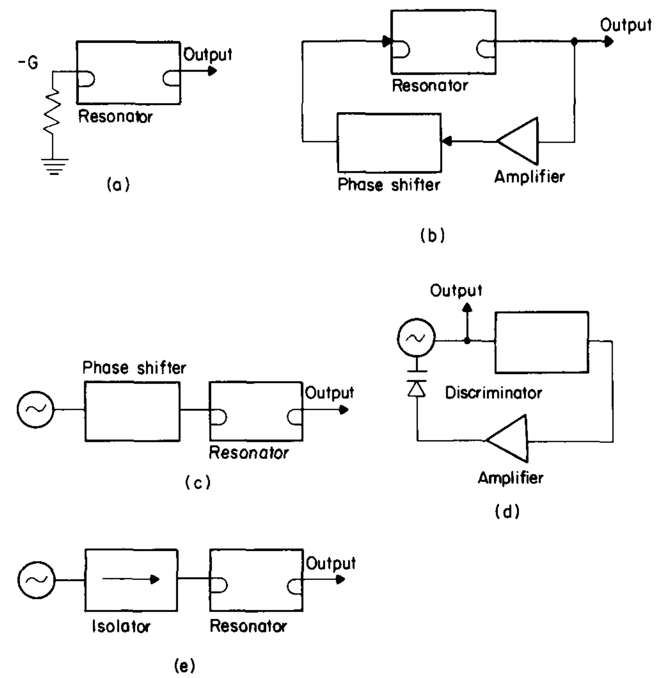

Fig. 2 Block diagram illustrating several superconducting frequency sources: a — negative resistance oscillator, b — loop oscillator, c — cavity-stabilized oscillator, d — stabilized-voltage-controlled oscillator, e — passive filter

The techniques discussed in this section 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.

Fig. 2b illustrates how an oscillator may be realized using a superconducting resonator and a unilateral amplifier (Khaikin,[13] and Viet[36]). Oscillation can occur when the amplifier gain exceeds the losses and the total phase shift around the loop is a multiple of 2π radians. 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. 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

$$\Delta\nu/\nu = \Delta\phi/2Q_{\mathrm{L}}. \qquad (3)$$

The phase changes due to factors such 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 possible 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 lines. It has been proposed to use a cryogenic travelling wave maser in a unilateral amplifier design (Higa,[10]). Alternatives are 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 bi-lateral, they can simply be connected to the superconducting cavity through an impedance transforming network as shown in Fig. 2a. (Jimmez and Septier,[12]). When the negative conductance of the amplifier exceeds the positive load conductance of the resonator, oscillation results. 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 450 K at 9 GHz (Uenohara,[35]). In addition, the very low operating voltage limits the theoretical output power to 1 mW at 10 GHz from commercially available devices (having peak current less than 20 mA). 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 20 K noise temperatures, and room temperature non-degenerate parametric oscillators have produced more than 100 mW at 9 GHz (Matthei and McCormick,[16]).

The most widely studied technique for realizing a superconducting oscillator has been the stabilization of a free-running oscillator with a superconducting resonator. One technique for accomplishing this, called cavity stabilization, is shown in Fig. 2c (Jimenez and Septier,[12]). 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, is given by 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 centre of the resonance is proportional to the line length between the oscillator and the cavity, just as in the loop oscillator.

The most successful superconducting oscillator technique to date is the use of active feedback to stabilize a voltage-controlled oscillator (Stein and Turneaure,[27]). The superconducting resonator forms the frequency sensitive element of a discriminator which generates an output voltage proportional to the frequency difference between the oscillator and the centre of the superconducting cavity resonance. 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.

Fig. 2e shows a superconducting resonator being used to filter the output of an oscillator. This application is particularly important when the oscillator is to be used as a source for frequency multiplication. For example, a state-of-the-art quartz crystal oscillator may be multiplied to 0.5 THz 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 equal to 2×10^9, it could in principle be multiplied to 100 THz (Walls and DeMarchi,[37]).

The conclusion of the above discussion is that two types of superconducting oscillators appear most promising for improved stability: stabilization of a VCO and the all-cryogenic 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 active 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.

Oscillator performance. The best superconducting oscillator frequency stability to date has been obtained by stabilizing a free-running VCO using the system of Fig. 2d. The measured time domain stability of a single superconducting oscillator is shown in Fig. 3 (Turneaure,[28]). 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 3×10^{-16} for times longer than 10 s. 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 $S_\phi(f) \simeq 7 \times 10^{-13}$ rad^2/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 behaviour 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-performing superconducting oscillator system.

Although this performance is excellent, there are several applications 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-cavity negative-resistance oscillator and the superconducting-cavity maser oscillator provide an opportunity to minimize external perturbations, since all their critical components are contained within the very stable cryogenic environment, perhaps making it possible to come closer to the frequency stability limits determined by thermal noise and the filtering action of the superconducting resonator. A projection of the potential of superconducting oscillators within the next decade would be a stability of 10^{-15} at 10 ms with a noise floor of 10^{-17}.

Applications

All of the uses of superconducting cavities which will be discussed here result from their low electromagnetic losses. However, substantially different advantages can be gained from this one property. There are applications where it is desirable to reduce the large amounts of power which would be dissipated in conventional devices. A second group uses the very high Q to realize exceptional filter characteristics, such as narrow bandwidth and high ratio impedance transformation. The low losses mean that practically any object placed in a superconducting cavity will determine its performance. Thus many materials properties may be accurately transduced as a frequency with high resolution and low noise. As a result of their state-of-the-art performance, superconducting oscillators are beginning to find a wide variety of applications either directly as clocks, as components of oscillator systems, or in a variety of physics experiments involving clocks and time. Finally, there are some special applications which are rather unique and are discussed separately from all the others.

High power devices. The performance of conventional linear electron accelerators is limited in the areas of duty factor and accelerated electron-beam current, energy stability, and energy resolution by the power which is needed to maintain the accelerating fields. For the linear accelerator at SLAC (Stanford Linear Accelerator Center) in the USA, 5×10^9 W is required for an electron to reach an energy of 20 GeV in a distance of 3000 m. In order to limit the average energy consumption to acceptable levels, the accelerator is operated with a duty factor of about 10^{-3}. The power required by superconducting cavities is about 10^6 times smaller than required for a conventional structure. Taking into account the efficiency of heat extraction at 2 K, which is 5×10^{-4}, a superconducting accelerator would require only 0.2% of the power needed by a conventional machine (Turneaure,[31]). The superconducting accelerator could be operated continuously with improvements in all the areas which were mentioned above. Similar advantages are obtained in the case of proton and heavy ion accelerators.

Many accelerators produce secondary particle beams with very high momentum and duty factor. Conventional rf particle separators require as much as 10 MW of rf power for these high-momentum particles, but suitable high-power microwave tubes are not available and the separators must be operated with low duty factor. Superconducting-cavity particle separators would make continuous operation possible. One has built and installed at CERN.

A potentially very important application which is beyond the present state-of-the-art of superconducting technology is the confinement of high temperature plasmas. The small losses in superconducting cavities could make an important contribution towards achieving the break-even point in the generation of thermonuclear fusion power from an rf confined plasma. The confinement problem requires peak surface magnetic fields of 10^4 0e within the microwave cavity; this is one order of magnitude higher than has been achieved to date (Turneaure,[31]).

Filters. Perhaps the most obvious application of high Q superconducting cavities is narrow band filtering. Below approximately 100 MHz, lumped element resonators are preferred, but at higher frequencies various types of cavities are used: helical structures between 500 MHz and a few GHz to 10 GHz or more; and Fabry-Perot resonators at higher frequencies. In addition to the obvious advantage of

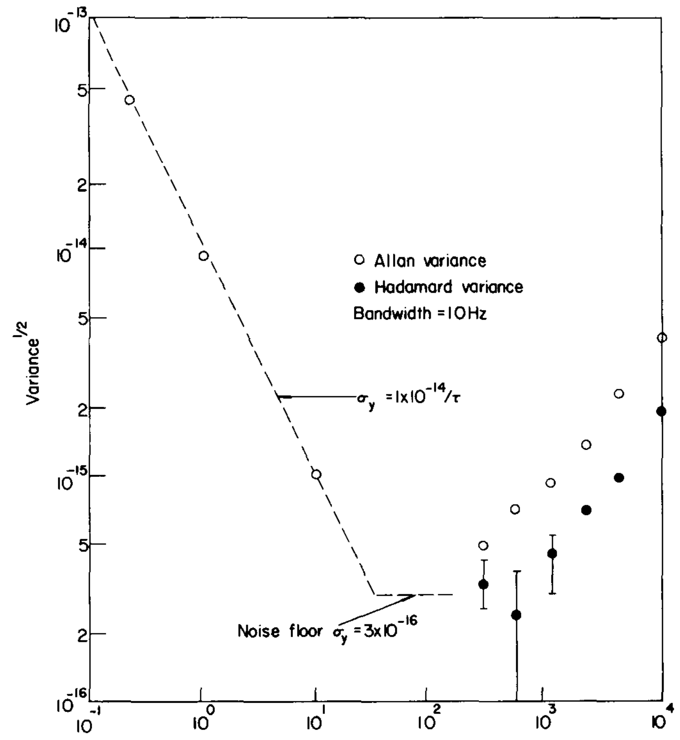

Fig. 3 The fractional frequency fluctuations of a superconducting-cavity stabilized VCO[33]

very narrow bandwidth, for example, 0.1 Hz at 10 GHz, cavities have very pure resonance modes. The geometry can often be chosen so that spurious modes are separated by an octave or more. In contrast, quartz filters have spurious modes usually spaced only 0.1% from the desired mode.

Superconducting cavities can be mechanically tuned over a wide range, but the instability introduced by the tuning mechanism seriously diminishes the stability of the resonator. Very fine, stable tuning can be achieved by controlling the temperature of the resonator - - the total fractional tunability is of the order of 10^{-10}. Similar tunability can be achieved by coupling an electronically variable reactance to the cavity. Another method which yields a tuning range of 10^{-4} is optical tuning by the photodielectric effect (Stone, Harting and Baker). This has been realized by placing a high-resistivity semiconductor wafer in the gap of a quarter-wave re-entrant cavity (where the rf electric field is very high). When a light beam is directed on the semiconductor, its dielectric constant changes, thereby producing a large shift in the cavity resonant frequency. Step changes in the frequency can be made in less than 10 ms, but the presence of the semiconductor degrades the bandwidth of the filter: a Q of 10^6 at 1 GHz has been achieved for such a device.

The narrowband, tunable filters which can be realized with superconducting cavity filters may be applicable to some communications or radar receivers, but it is more likely that they will be used in highly specialized devices. For example, a superconducting resonator may be used to obtain strong coupling between an evaporated Josephson junction and an electromagnetic field (Smith,[23]). This is particularly valuable when the junction is used as an oscillator. If such a junction is not incorporated into a resonant structure, the large shunt capacitance shorts out high frequency voltages. The theoretical maximum output power from a Josephson junction is $0.58\,I_0\,V$, where I_0 is the critical current and V is the bias voltage. Theoretically, a typical junction can emit about 10^{-7} W at X-band, but only about 1% of this is observed from waveguide-coupled evaporated junctions. In addition to performing the required impedance matching to the junction, the superconducting resonator also provides narrow-band filtering of the output signal. Unfortunately, this property detracts from the major advantage of the Josephson junction oscillator, it has a tuning sensitivity 10^5 times greater than conventional oscillators (Silver,[22]). In order to preserve this property, it would be necessary to use superconducting cavities with extremely agile frequency tuning.

Superconducting resonators may also be useful as high-ratio impedance transformers for use with superconducting antennas. This application also has the disadvantage of narrow bandwidth. Superconducting antennas are not considered advantageous over conventional devices (at least for today) (Silver,[22]).

Transducers. Superconducting cavities make attractive transducers for a variety of quantities because they introduce negligible perturbations and their output is usually in the form of an easily and accurately measured frequency. Since the frequency of a cavity resonator is approximately inversely proportional to one of its dimensions, it is very natural to use such a resonator to measure changes in that length. The resolution is limited by the frequency instability of the resonator; the best achieved stability of superconducting cavity oscillators corresponds to a random noise level of 3×10^{-16} cm. This performance can be improved, in principle, by designing the resonator so the controlling dimension is very small. It has been predicted that a quarter-wave re-entrant cavity would permit the resolution of 10^{-17} cm for one-second integration time (Dick and Yen,[4]). However, it has not been demonstrated that the necessary Q can be obtained with such a resonator design. There is an interest today in superconducting cavity length transducers for the detection of gravity waves. In such an experiment, the cavity itself could be used as the antenna, but more likely two cavities would be coupled to a traditional bar antenna in a way which would cancel a substantial fraction of the frequency noise in the exciting oscillator.

Substantial use has been made of superconducting cavities to measure a variety of properties of materials at low temperature. The technique is to place a sample within the resonator and to measure either the frequency or Q as a function of the parameters of interest. The advantage of this technique is that it does not require ohmic contacts and can be used with randomly shaped, powdered or liquid samples. Dielectric constants very near unity and loss tangents as small as 10^{-9} can be measured because of the high stability and very low losses of the superconducting cavity itself (Hartwig and Grissom,[9]). Many semiconductor properties have been measured including relaxation time, lifetime, Fermi level, trap ionization energy, trap density, capture cross section, trap population, and free carrier density (Hinds and Hartwig,[11]).

Some properties of liquid helium have also been studied this way. The thermal expansion has been measured with a sensitivity, in terms of fractional density change, of 4×10^{-9} (Berthold, Hanson, Maris and Seidel,[2]). This sensitivity is sufficient to yield quantitative data concerning the dispersion relation for thermal phonons in liquid helium. The damping of oscillations of the liquid helium through a small orifice can be studied using the frequency of a superconducting cavity to sense the level of liquid helium within it. This data has been used to study the quantization of vorticity in superfluid helium (Trela,[29]).

Several interesting and useful devices can be implemented using superconducting cavities. A thermometer can be made for the temperature range from 0.25 to 0.6 K by filling a cavity with He^3 vapour in equilibrium with the bulk liquid. Changes in density, which are reflected in frequency changes, are interpreted in terms of the temperature of the gas. In this range, the accuracy of the temperature reading of such a thermometer is estimated to be 0.2% (Berthold, et al.,[2]). A nuclear radiation detector can be made by placing a properly doped semiconductor crystal on the stub of a quarter-wave re-entrant cavity. Below 70 K, the charge carriers created by the absorption of radiation are trapped for very long times at sites in the forbidden band. As a result, the frequency of the cavity shifts in proportion to the total absorbed dose. A detector for low levels of light can be implemented in a similar way, only in that case the frequency shift results from the photodielectric effect.

Oscillators and clocks. The excellent spectral purity and medium term stability (up to about one day) of superconducting oscillators have numerous applications. In the following discussion these are divided into three categories: oscillators used as components of instruments; oscillators used as clocks to provide timing functions for complex instrument systems; and oscillators used to perform experiments based directly on clock performance.

Oscillators with very good spectral purity (short term stability) are important elements of many instruments and measurement techniques. One example is the use as the starting oscillator for frequency multiplication from microwave to infrared or higher frequencies. The process of multiplication by an integer n increases the phase noise power by $n2$. This creates a severe practical problem because once the integrated white phase noise becomes comparable to 1 rad, it is no longer possible to identify the coherent signal component. Superconducting oscillators have two important advantages in this application: they can operate at frequencies at least as high as 10 GHz, and theoretically they can produce a signal whose spectral purity is limited by the characteristics of the multiplier. For example, it has been predicted that a state-of-the-art commercial 5 MHz quartz crystal oscillator may be multiplied to 0.5 THz before the carrier is lost, but the same signal when filtered by a 10 GHz superconducting cavity with $Q = 10^{10}$, can be multiplied directly to 100 THz.

Certain types of radar also depend critically on the spectral purity of their local oscillator. Return signals from nearby stationary clutter mix with the phase noise sidebands and limit the signal to noise ratio of the true Doppler signal. For example, if a 1 GHz radar has target velocity detection down to 40 m/s and Doppler bandwidth of 10 kHz, then in order to achieve 80 dB sub-clutter visibility, it is necessary to use a local oscillator the phase noise of which is more than 120 dB below the carrier for Fourier frequencies greater than 200 Hz.

A third application for short term stable oscillators is as flywheel oscillators in atomic frequency standards. Since the time domain frequency stability, $\sigma_y(\tau)$, cannot improve faster than $1/\tau$, the medium term performance of the standard is limited by the flywheel oscillator if its stability is worse than that of the atomic frequency discriminator at the attack time of the feedback loop. Quartz crystal oscillators do not degrade the performance of current atomic standards, but if expected improvements in these standards are made, then improved flywheel oscillators will be needed and superconducting oscillators are a possible candidate. Flywheel oscillators are also used for autotuning hydrogen masers, a process whereby cavity pulling and spin exchange frequency shifts are simultaneously reduced. Present autotuning systems utilize a pair of masers, one of which could be replaced by a superconducting oscillator (Peters, McGunigal and Johnson,[19]).

Superconducting oscillators can also be used to provide time for complex instrumentation and measurement systems such as radio astronomy and radar ranging. The desirability of superconducting oscillators for these applications range from cost savings to the potential for significant improvements in performance.

Very long baseline interferometry (VLBI) using independent clocks may have the following clock performance requirements for certain types of experiments: initial 1 μs synchronization of the start of recording; total time error of less than 1 ns over a five hour observation period to insure that all the data have the same initial offset error; and sufficient coherence to guarantee that the recorded signals can be cross correlated (Klemperer,[14]). For a 10 GHz system and an observation time of one hour, the coherence requirement is met by an oscillator with a noise floor $\sigma_y = 5 \times 10^{-15}$. The required noise floor decreases inversely with both the operating frequency and the observation time. The current requirements are met by both hydrogen frequency standards (active and passive devices) and superconducting oscillators.

Various types of navigation systems need state-of-the-art clocks. Since both the navigation requirements and the techniques are somewhat flexible, it is difficult to place fixed requirements on clock performance. Typical performance goals for two navigation systems are discussed here.

The NASA Deep Space Net utilizes a network of radar stations to track spacecraft which have left earth orbit. The current capability of the system is $\sim$ 5 m range resolution and 1 μrad angular resolution. Planners foresee the need for approximately an order-of-magnitude improvement in resolution for some missions which will be flown in the early 1980's, such as the Jupiter Orbiter (JOP). The clock stability requirements depend on the method of range measurement. One approach which has been suggested is to replace most of the coherent (two-way) Doppler ranging with non-coherent (one-way) Doppler measurements. The latter technique, also called wideband VLBI, has the advantage that it substantially reduces the tracking time taken to achieve an accuracy comparable to current coherent tracking methods. However, it places the most stringent requirements on clock performance of any ranging system. When daily calibrations are used, the frequency must be constant to 1.5×10^{-14} over one day.

Weekly calibrations are preferable to reduce cost and calibration time, but the frequency stability requirement becomes 3.2×10^{-16} over one day.

An experiment has been proposed to use the DSN to detect gravitational waves. The passage of a gravitational wave pulse past the earth and spacecraft produces an identifiable signature in the range information. This experiment places very difficult stability requirements on the frequency standards. To do a feasibility experiment, the frequency stability must be 3×10^{-16} for the duration of the experiment, 40 s to 4000 s. This can be achieved with a state-of-the-art superconducting oscillator system. An experiment, sufficiently sensitive to detect theoretically predicted gravitational pulses, would require frequency stability of 3×10^{-18}. It is possible that a superconducting oscillator using a cavity with $Q = 10^{11}$ would eventually be capable of reaching this performance level.

The Global Positioning System is a multisatellite system intended to provide earthbound navigation with a precision of several meters by using the time of flight between the user and several satellites. Each satellite carries high-stability clocks which need to keep time to a few nanoseconds over many days. Several hydrogen frequency standards are being developed for possible future use. Depending on future system requirements, superconducting oscillators could be useful for this application.

There are several fundamental physics experiments which are based directly on superconducting oscillator performance. Two of these, a red shift experiment and a fundamental constants experiment, are performed by comparing the frequency of a superconducting oscillator to the frequency of an atomic standard based on a hyperfine transition such as cesium or hydrogen. In the red shift experiment, one looks for a term in the frequency ratio that has a period of one solar day. Because of the earth's rotation in the sun's gravitational field, various theories of gravity predict.

$$\frac{\nu_{\text{hyperfine}}}{\nu_{\text{superconducting}}} = A\ [1 + 10^{-12}\ (\Gamma_0 - \tfrac{1}{2} T_1)\ \cos(2\pi t/1 \text{ solar day})],$$

where Γ_0 and T_1 are zero for any metric theory of gravity such as the general theory of relativity. With available standards it would in principle be possible to set an upper limit of 10^{-3} on $\Gamma_0 - \tfrac{1}{2} T_1$. The Eotvos experiment already places a limit of 10^{-8} on Γ_0 and may place a limit on T_1.

If instead of analyzing the data for diurnal effects, thay are fit to a linear drift model, then the same experiment may be analyzed to yield an upper limit on the time rate of change of the fine structure constant. The ratio of the frequencies of a hyperfine standard to a superconducting oscillator is

$$\frac{\nu_{\text{hyperfine}}}{\nu_{\text{superconducting}}} = Bg\left(\frac{m}{M}\right)\alpha^3$$

where m is the mass of the electron, M is the mass of the nucleus and g is the gyromagnetic ratio of the nucleus; B is a constant. By comparing a superconducting oscillator to a cesium standard for 12 days, it has been determined that $(1/\alpha)\ (\mathrm{d}\alpha/\mathrm{d}t)$ is less than 4×10^{-12}/year with 68% probability (Turneaure and Stein,[32]). The quality of this experiment was limited by the data link connecting the laboratories where the standards were located. Significant improvements may result from a comparison of superconducting oscillators and hydrogen standards in the same laboratory. Although astronomical and geophysical measurements have set a tighter upper limit, they have the disadvantage of averaging possible changes over periods of the order of 10% of the age of the universe.

A laboratory experiment has been proposed to use a superconducting resonator excited by a superconducting oscillator to measure the Lense-Thirring effect - - the dragging of inertial frames by a rotating mass (Braginsky, Caves, and Thorne,[3]). A toroidal superconducting waveguide is centred on the rotation axis of an axisymmetric object. The wave travelling in the same direction as the rotating body takes less time to complete one round trip than the counterrotating wave. As a result, the interference pattern rotates around the waveguide. For a 5000 kg mass with 50 cm radius rotating at an angular velocity of 2×10^3 rad/s, the angular velocity of drag has been estimated to be 2×10^{-20} rad/s. The required waveguide Q is 5×10^{16} and the stability of the exciting oscillator must be 1×10^{-17}. This stability is probably achievable, but it is difficult to say whether such high Q's can be achieved.

Special devices. Occasionally superconducting cavities can be used to solve some unusual problems. One example of this is the reduction of the cavity phase shift problem in cesium beam frequency standards. At the present time, the most significant limitation in the accuracy of cesium beam frequency standards is the extent to which the phase difference of the rf fields in the two interaction regions can either be nulled or measured. If superconducting cavities were used, the variations of the microwave phase across the apertures of the cavities would become very small and it would be possible to measure the intercavity phase shift with high precision. This approach is not being tried at the present time.

Another novel suggestion is a superconducting cavity gyroscope. One possible configuration is the toroidal microwave cavity which was described earlier in the discussion of the Lense-Thirring effect. The position of the nodes in such a cavity experiences a phase shift proportional to the rotation speed of the cavity and the frequency of the exciting radiation. This is just the Sagnac effect which is used today in laser gyroscopes. Because of the difficulty in optical detection of fringes, laser gyroscopes are constructed today in the form of ring oscillators. These devices must be biased in order to overcome a dead zone at low rotation rates; systematic errors introduced by the bias degrade the performance of the gyroscope. The superconducting version of such a gyroscope is less sensitive by a factor of 10^4 to 10^5 because of the wavelength difference. However, this is offset by the fact that it is possible to detect a much smaller fraction of a fringe at 10 GHz than at visible frequencies. Consequently, it may be possible to construct a Sagnac-type gyroscope (using superconducting cavities) which operates in the interferometric mode with no dead zone and is competitive in sensitivity with the best mechanical gyroscopes.

Summary and conclusions

There are documented needs for superconducting cavities with Q's up to 10^{17} and for superconducting oscillators with stabilities as good as 3×10^{-18}. The best Q achieved to date is 5×10^{11} and the best stability is 3×10^{-16}. Since it is possible to find the centre of a resonance line to better than one part per million, it is reasonable to expect that a stability of 2×10^{-18} will be achieved using present technology, and this might be accomplished within ten years.

The most intriguing potential space application of these oscillators is their use for ranging. The possibility that gravitational radiation might be detected by more sensitive ranging to a drag-free satellite should warrant careful consideration. Cavity-stabilized oscillators must surely be considered if large improvements are needed for deep space tracking or satellite navigation systems. Present performance of the superconducting oscillator is impressive, but the potential for improvement puts this system into a class of its own. Most work in progress on these oscillators is directed toward application of the devices to real problems without concern for further major improvements in performance levels. Stimulation of work toward improved performance will have to be driven by applications which require such improvement.

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