SUPERCONDUCTOR-SAPPHIRE CAVITY FOR AN ALL-CRYOGENIC SCSO

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Abstract

To develop a superconducting cavity stabilized oscillator (SCSO) as a frequency standard, we are studying the properties of cavities consisting of a single crystal of sapphire surrounded by a superconducting film. Measurements of quality factors of spherical and cylindrical samples of sapphire are reported. Loss values less than 2×10^{-9} have been measured at a temperature of 1.45K.

A design for an all-cryogenic SCSO is described, with particular emphasis on the cavity requirements. We conclude that such a design would allow greatly enhanced stability of operation due substantially to the thermal and physical properties of the sapphire substrate. Cavity Q requirements are relatively modest, with better than 10^{-16} frequency stability predicted for a Q of 10^8.

Introduction

Improvement in the precision of time measurement would benefit many scientific activities. At the Jet Propulsion Laboratory, time measurement accuracy determines how well satellites can be navigated, and how well radio sources can be located, to name but two of the applications. This report concerns developments toward a superconducting cavity stabilized oscillator of sufficient stability to improve the precision of time measurements.

The best stability performances to date, excluding SCSO, have come from atomic maser devices. Figure 1[1] shows the frequency stability available for such devices plotted against the averaging time for the measurement. Also shown are the goals set for the NASA Deep Space Network (DSN) to provide tracking accuracy required for scientific experiments envisioned for the near future. These requirements are brought out more explicitly in Figure 2[1], which shows, in addition to the fractional frequency stabilities, the corresponding tracking accuracy at Jupiter for an earth-based station. Figure 2 also shows the prospects for improving the frequency stabilities of various oscillator systems. Note that the improvements expected for the hydrogen maser barely meet the 1986 goal stability level, and do so over only a fraction of the averaging times required. The trapped mercury ion device is not expected to be available until 1990, and then, if projections hold true, will meet the 1990 goal only for integration times near a day and longer. In this paper we shall discuss our approach to a SCSO design that is expected to improve on the stability levels and drift properties shown in Figure 2, and the progress made toward producing resonators for such a SCSO.

The Oscillator Design

For an SCSO, mechanical and thermal effects are as important toward inducing frequency fluctuations as the electrical perturbations in the active element. Therefore, our cavity design uses a single crystal of high quality sapphire coated with a superconducting film[2] to

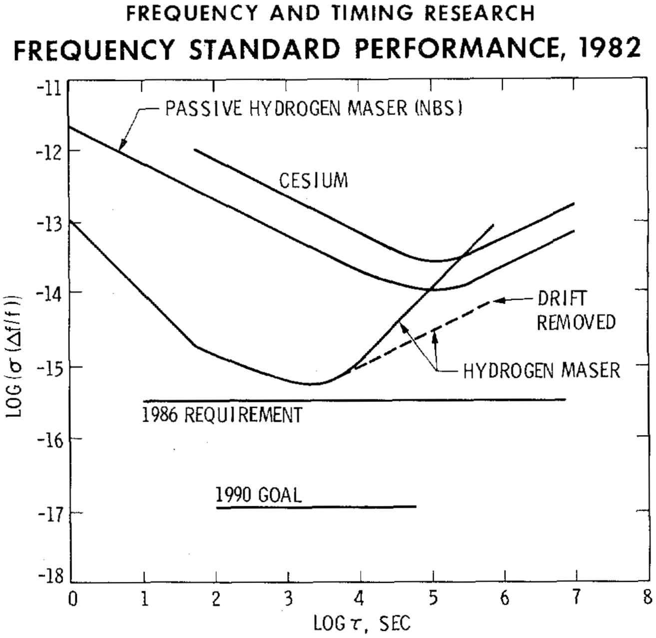

Figure 1. Square root of the variance of frequency fluctuations versus the averaging time for several oscillator systems. Also indicated are the stability level goals of the NASA Deep Space Network for the years 1986 and 1990.

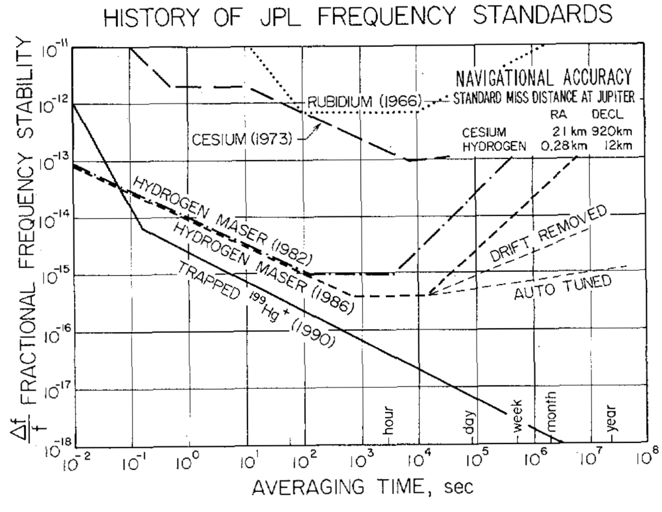

Figure 2. Square root of the variance of frequency fluctuations versus the averaging time for several oscillator systems. Proposed improved oscillator stabilities are also shown. The inserted table indicates the impact that present stability levels have on spacecraft navigation.

Manuscript received November 30, 1982

provide the excellent mechanical and thermal stability required. With a ruby maser as the negative resistance device and a metal-coated ruby waveguide to link the cavity and maser as shown in Figure 3, all critical elements in the oscillator consist of similar materials. Since both the cavity and the ruby maser perform best at low temperature[3], the entire oscillator will be cooled to below 1 Kelvin.[3]

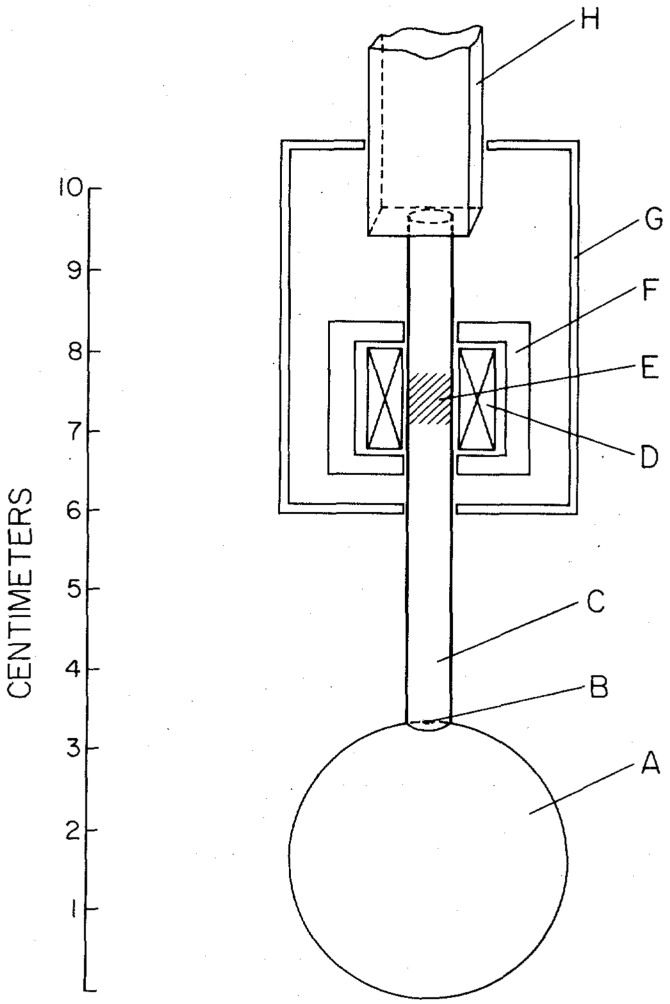

Figure 3. An all-cryogenic superconducting cavity stabilized oscillator configuration. The superconductor-on-sapphire resonator A is coupled through iris B to the metal-coated ruby waveguide C. A superconducting solenoid magnet D creates the "active" region E in the ruby where the energy level spacing of the chromium ions matches the resonator frequency. Pole piece F and superconducting shield G confine the magnetic field away from the resonator. Oscillations are induced by masing action in the active region when pumped by the higher frequency signal transmitted by waveguide H. A port coupling the oscillator signal itself is not shown; also not shown are additional magnetic shields. Typical values: for a resonator of diameter 3.5 cm resonant at 4 GHZ, a magnetic field of .32 tesla and a pump frequency of 29 GHZ are required.

The low noise properties of the maser, the uniform and precisely controllable cryogenic environment and the stable, matched materials will all combine to provide an ultrastable oscillator. Even so, consideration must be given to vibration isolation, thermal stabilization, gravitation-induced distortions and other perturbations. Our method, invoking measures to reduce these effects, provides potential improvements over previous SCSO's ranging from factors of 10 to 1000 for the various disturbances.

Figure 4 shows the expected stability performance of our SCSO. For short averaging times, the stability is limited by the white phase noise in the amplifier following the oscillator with a variance that obeys the relation[4]

$$\sigma^2 = \frac{S(f)B}{\tau^2} \qquad (1)$$

where

σ^2 = variance of fractional frequency fluctuations (dimensionless)
$S(f)$ = the spectral density of phase fluctuations in the amplifier = constant (for white phase noise) (Hz^{-3})
B = measurement bandwidth (Hz)
τ = averaging time of the measurement (seconds)

and the special case of using differences of successive samples and sampling at time intervals equal to τ has been assumed.

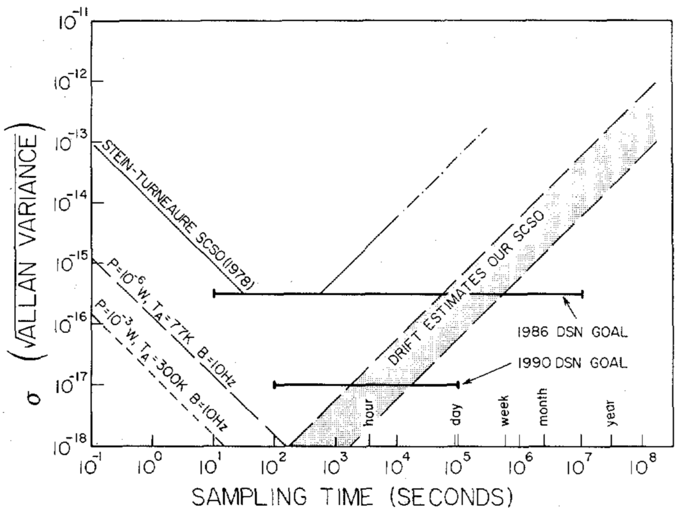

Figure 4. Square root of the Allan variance for two SCSO systems versus the sampling time. The dashed curve is the limit of stability for an oscillator driven at 10^{-3} watt power level, while the solid line represents the measured values for the Stein-Turneaure SCSO[5] operated at that power. The broken lines bound the possible stability levels of our SCSO. The noise temperature of the following amplifier for the Stein-Turneaure SCSO was 300K; our SCSO is assumed to have an amplifier with 77K noise temperature. A bandwidth of 10 Hz is assumed. Also shown are the NASA Deep Space Network stability goals for 1986 and 1990.

The curves at small τ in Figure 4 represent σ for oscillator powers of 10^{-3} watt (dashed curve) and 10^{-6} watt (broken line) for a bandwidth of 10 Hz and amplifier noise temperatures indicated. Also shown are the measured values of τ reported by Stein and Turneaure[5] for a SCSO (hereafter called SCSO I) consisting of a cylindrical TM_{101} niobium cavity at low temperature and X-band electronics at room temperature. Although the stabilities obtained by SCSO I are the best ever reported for any oscillator, Figure 4 demonstrates that the performance was far from the stability limit for the oscillation power level of 10^{-3} watt. Additionally, rather high levels of drift plagued their oscillator, giving the increasing instabilities shown at large τ.

Our design aims to reduce the response of the oscillator to the numerous perturbing influences. Though operation at 10^{-6} watt implies a higher limit of σ at short sampling times, the limit is still far better than the performance of SCSO I, and we expect that this limit can be approached with our design. The lower power level reduces sensitivity to radiation pressure fluctuations by a factor of 1000 and allows low temperature operation. The sapphire substrate and lower operating temperature reduce sensitivity to temperature fluctuations by more than 100. The mechanical strength of the sapphire and its low density combine to reduce sensitivity to gravitational variations and other accelerations by a factor of 10; mounting techniques can reduce this response by a further factor of 10 or more.

Thus, the broken lines in Figure 4 represent the estimated stability levels obtainable with our SCSO. The authors conclude that the short-τ region of the SCSO I data represents response to vibrations[5]; our SCSO design should be 10 to 100 times less responsive to accelerations. In the long - τ region the drift shown for SCSO I should be reduced for our design by factors of 100 to 1000 due to the aspects listed above.

Effects Due to Cavity Q

A high quality factor Q for the resonant cavity is required to obtain a narrow resonance line width and good frequency stability in the oscillator. Both the sapphire material and the superconducting film applied to it must be sufficiently free of loss to allow the Q values of 10^8 or larger that yield oscillator frequency instabilities below 10^{-16}.

The high cavity Q reduces frequency drifts due to three sources: the noise of the feedback amplifier, drifts in amplifier characteristics, and variations in waveguide length. Variations due to amplifier noise are given by

$$\sqrt{\sigma^2} = \frac{1}{Q}\sqrt{\frac{k_B T_a}{P}}\,\frac{1}{\sqrt{\tau}} \quad , \qquad (2)$$

where k_B is Boltzmann's constant, P is the oscillation power, T_a is the amplifier noise temperature, and τ is the averaging time. For a noise temperature of 3K and power of 10^{-6} W, this becomes

$$\sqrt{\sigma^2} = \frac{6.5 \times 10^{-9}}{Q\sqrt{\tau}} \; . \qquad (3)$$

Maser amplifier characteristics are sensitive to the magnetic field, since the bandwidth is relatively small, corresponding to a maser amplifier quality factor $Q_m \approx 50$. Frequency drift would be approximately

$$\sqrt{\sigma^2} = \frac{Q_m}{Q}\,\frac{\Delta H}{H} \; , \qquad (4)$$

where ΔH is the instability in the maser magnetic field H.

A superconducting magnet in a persistent mode surrounded by a superconducting shield is expected to provide the required stability for the magnetic field.

Finally, variations in waveguide length due to temperature fluctuations give rise to frequency variations as

$$\sqrt{\sigma^2} = \frac{2\Delta L}{Q(\lambda/2\pi\sqrt{\varepsilon})} = \frac{4\pi\sqrt{\varepsilon}}{Q\lambda}\,k\Delta T \qquad (5)$$

where ΔL is the change in waveguide length L, ε is the dielectric constant of sapphire, λ is the wavelength in free space and k is the coefficient of thermal expansion of the sapphire waveguide

$$(\sim 5 \times 10^{-13}/\mathrm{K} \text{ at } 1\mathrm{K})^2 .$$

Substituting typical values for other parameters this becomes

$$\sqrt{\sigma^2} = \frac{1.9 \times 10^{-12}}{Q}\,\Delta T . \qquad (6)$$

Therefore, a Q of 10^8 or larger will allow a stability of 10^{-16} to be achieved, although higher Q values are desirable to reduce sensitivity to magnetic disturbances.

Sapphire Loss Measurements

The first sapphire materials, obtained as off-the-shelf spheres (2.54 cm diameter)[6], gave the quality factors shown with x's in Figure 5. These Q values were measured in two ways. First, the sapphire sphere was coated with an evaporated Nb film, leaving small coupling apertures, and the decay time of the resonant TE_{101} mode at 3.49 GHz was measured; second, an uncoated sphere was placed inside a lead-coated cavity and various resonant modes excited in the sphere, again noting the decay times. The data of Figure 5 were obtained by the first technique, while the second technique, verifying the values obtained by the first, showed that the losses should be attributable to the sapphire material, and not to the Nb film.

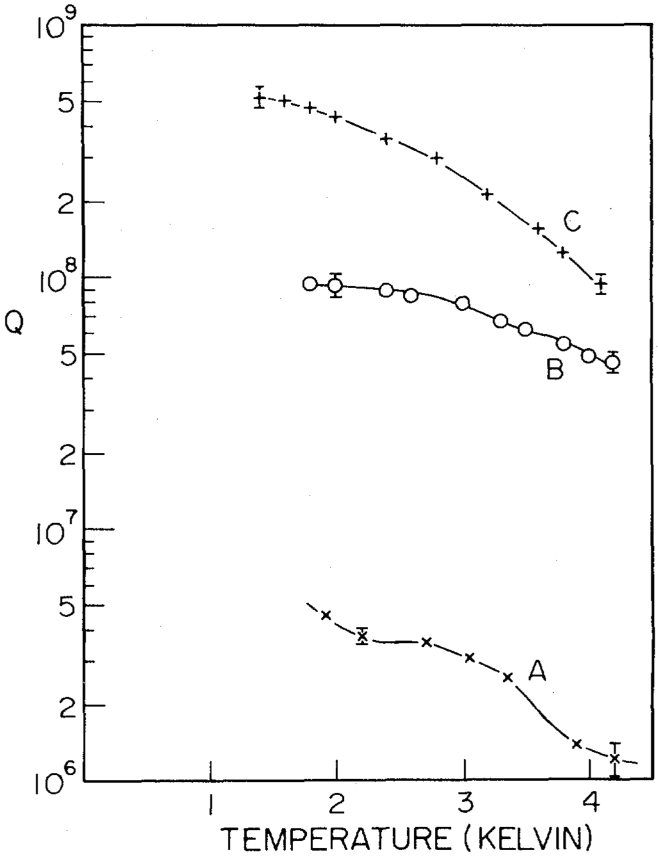

Figure 5. Quality values Q for various single crystal samples of sapphire. Curve A: a sphere of diameter 2.54 cm, purchased "off-the-shelf" from Adolf Meller. Curve B: a cylinder purchased from Crystal Systems. Curve C: a cylinder purchased from Union Carbide. The lines drawn through the data points are only guides to the eye, representing no function. Representative error bars are shown on several data points.

Two other samples of sapphire were obtained[7,8] as right circular cylinders with diameter and length both equal to 3.81 cm and with the cylinder axis as the crystal c-axis. A Pb-plated copper cavity, whose own Q values reached 3.7×10^9 at 1.6 Kelvin (at 7.79 GHz), was used to measure the losses in these samples. The results obtained at 2.79 GHz are shown in Figure 5. The best results for the Union Carbide sample at 1.45 K represent a level of loss for the sapphire of less than 2×10^{-9}. One of these samples is presently being formed into a sphere to allow a superconducting film to be deposited. Such a superconductor-on-sapphire configuration is required to reduce the thermal expansion coefficient of the entire cavity, and will be tested soon.

Conclusion

The need for improved oscillator stability is evidenced by, for example, the topics being discussed at the concurrent Precise Time and Time Interval Conference. One specific application has been cited in this paper; many other experiments or applications could be improved by either more stable oscillators or better time measurement precision. Our present design goal aims at optimizing the performance of our SCSO for measurement times in the range 10^2 seconds to 10^4 seconds. Some flexibility is available to optimize for other measurement times required by other applications.

To reduce the effects on the frequency stability of various perturbing influences, cavity Q must attain a sufficiently high level. We have demonstrated that sapphire substrates of adequate quality can be obtained for the cavity. The superconducting films which we deposited on the cavity used to test the sapphire dielectric loss have also been shown to be adequate. As a next step, we intend to develop adequate superconducting films deposited directly on the sapphire sphere.

The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

D. M. Strayer is a NRC Senior Resident Research Fellow at the Jet Propulsion Laboratory. The support of the National Research Council is gratefully acknowledged.

References

1. Data for Figures 1 and 2 were obtained from Dr. R. L. Sydnor, Supervisor, Time and Frequency Systems Group, Jet Propulsion Laboratory, and are gratefully acknowledged.
2. V. B. Braginski, V. I. Panov, S. I. Vasiliev, "The properties of superconducting resonators on sapphire", IEEE Transactions on Magnetics, MAG-17, pp. 955-957, 1981.
3. W. H. Higa, "The superconducting cavity stabilized maser oscillator", Technical Memorandum 33-805, NASA, 1976.
4. J. H. Shoaf, NBS Report 9794, p. 27, 1971.
5. S. R. Stein and J. P. Turneaure, Proc. Conf. on Future Trends in Superconductive Electronics, AIP Conf. Proc. No. 44, 192-213, 1978.
6. Adolf Meller Company, P.O. Box 6001, Providence, Rhode Island, 02904.
7. Crystal Systems, Inc., 35 Congress Street, Salem, MA 01970.
8. Union Carbide Corp., Crystal Products Dept., 8888 Balboa Ave., San Diego, CA 92123.