Ultrastable Performance of the Superconducting Cavity Maser Oscillator at Short Measuring Times

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Recent measurements performed on the superconducting cavity maser (SCM) oscillator show frequency stability in the range of 10^{15} for times from 1 sec to 1000 sec. Phase noise of approximately -80 dB/f^3 was also measured. This short- to midterm performance appears to be better than that of any microwave oscillator. In particular, the measured stability at 1-sec intervals is 10 times better than that of a hydrogen maser, and the phase noise at 8 GHz is more than 20 dB below that of the best multiplied quartz-crystal oscillators. A frequency pulling coil has been implemented and tested to enable the SCM to be slaved to a hydrogen maser at a time constant of approximately 50 sec. This combination will allow the long-term performance of the hydrogen maser to be improved by adding to it the newly available short-term performance of the SCM.

I. Introduction

The superconducting cavity maser (SCM) is a helium-cooled, all-cryogenic oscillator with superior stability at short measuring times [1–4]. It differs from other superconducting cavity stabilized oscillator (SCSO) designs [5–7] in its use of a very rigid ($Q \approx 10^9$) sapphire-filled stabilizing cavity and in its all-cryogenic design; excitation is provided by an ultra-low-noise cryogenic ruby maser.

A comparison of ultrastable atomic frequency sources shows active hydrogen masers to be superior to passive atomic frequency standards in short-term stability (1 sec $< \tau <$ 100 sec). Performance of the SCM at short measuring times is superior even to that of the active hydrogen maser. Like the hydrogen maser, the SCM is an active oscillator. The advantage of the SCM is its larger output signal power ($\approx 10^{-9}$ W versus $\approx 10^{-12}$ W for the hydrogen maser). Long-term performance is limited by variations of the operating parameters of temperature, drive power, output voltage standing-wave ratio (VSWR), etc., depending on the sensitivity of the SCM to these various parameters.

Figure 1 shows a diagram of the improved oscillator. The three-cavity oscillator, consisting of a ruby maser, a coupling cavity, and a high-Q lead-on-sapphire cavity, has been discussed previously [2]. Oscillation at a frequency of 2.69 GHz results from operating a ruby maser at a 13.1-GHz pump frequency, and a population inversion is created. Energy-level splittings in the ruby are matched to those of the high-Q cavity by means of a bias field provided by a superconducting solenoid. The frequencies of the three modes of the coupled-cavity system are spaced relatively close to each other (5-percent spacing) in order for them to couple effectively, but they are spaced far enough from each other to allow mode selection by adjustment of the bias field [2].

II. Experimental Aspects

Substantial technical improvements have been made to eliminate frequency instability due to operational parameters. These parameters are temperature, pump frequency, pump power, pump frequency polarization, temperature gradient, coupling strength, and output VSWR. Either the parameter has been stabilized or the coefficient that couples the parameter value to the operating frequency has been minimized.

The temperature dependence of the output frequency of the SCM shows an extremum in the range between 1 and 2 K [4]. From a functional point of view, the presence of the frequency maximum at about 1.57 K is an extremely desirable feature, since it allows operation of the oscillator in a region of gradually disappearing temperature coefficients. The quadratic coefficient of $\delta f/f$ at the maximum is $3.3 \cdot 10^{-9}/K^2$. Thus, a temperature accuracy of one mK together with a stability of 30 μK allows a frequency stability of $\delta f/f = 2 \cdot 10^{-16}$.

Frequency dependence on the frequency and amplitude of the microwave pump has also been studied [4]. Since the power of the pump is very much more difficult to stabilize than its frequency, a major feature of the results to date is a "valley" where the sensitivity to pump power is greatly reduced. In this region the slope is $\leq 2 \cdot 10^{-13}$/dB, which is a value 100 times smaller than was typically found.

Several recent improvements have made increased stability possible:

(1) Extension of operational period. The 1.57-K cooling system was changed from closed-bath refrigeration to continuous flow. The operational period was extended from three days to seven days; it is limited only by the storage time of the larger 4.2-K helium bath from which the small (continuous) flow is drawn. It is expected that this can be extended to 30 days with a better dewar. This change to a continuous-flow system also provides continuous operation of the SCM during helium transfer.

(2) Improved temperature stability. Temperature fluctuation has been minimized to 40 μK, a factor-of-1000 improvement. Prior to the improvement, a parabolic curve of oscillation frequency versus temperature was measured and had a frequency maximum near 1.57 K. With present temperature-control capacity, even a temperature offset of 100 mK would only degrade the frequency stability to $4 \cdot 10^{-14}$. The SCM has been operated in the region of a nominally zero temperature coefficient with a temperature accuracy of one mK.

(3) Reduction of the number of temperature gradients across the oscillator. Substantial reduction in thermal gradients was made by modification of the cryogenic temperature-control system. Gradients associated with the regulatory configuration were eliminated by consolidating the heating and cooling elements to allow a single thermal contact point with the oscillator assembly.

(4) More effective ruby pumping. A fixed rectangular waveguide was installed with the pump signal's B-field perpendicular to the ruby c-axis. This cryogenic polarizer should eliminate the primary remaining system uncertainty and allow reliable operation from run to run.

(5) Improved pump signal propagation. Elimination of a coaxial signal-transmission line within the pump waveguide now allows a more direct pump signal path. A waveguide adaptor was installed, and a teflon window was used as a vacuum seal and to allow low-loss microwave propagation. It is expected that less pump power will be required to obtain oscillation, since the unmatched impedance caused by the right-angle feed will be eliminated.

(6) Reduction of in-oscillator noise caused by back-coupling with the room-temperature amplifier. A cryogenic isolator[1] has been installed to prevent room-temperature radiation from coupling into the oscillator and also to reduce the sensitivity of the operational frequency to output VSWR.

III. Measurements

The improvements discussed above have made possible excellent stability at both relatively long (10,000-sec) and very short (1-sec) measuring times. In order to characterize the performance of the SCM at the shorter times, another cryogenic oscillator (the SCSO) was obtained for use as a frequency reference [5,6]. Substantial improvement in other instrumentation was also necessary. New procedures

[1] The cryogenic microwave isolator was made by Passive Microwave Technology, Inc. Its center frequency is 2.7 GHz with 30-dB isolation.

included bypassing the receiver of the SCSO in order to make direct measurements of the two microwave frequency signals. Long-term measurements primarily made use of a hydrogen maser as the frequency reference.

Figure 2 shows raw data for tests of the SCM against SCSO and hydrogen maser references. The filled circles represent data of the SCM/SCSO test, and the open circles represent the SCM/hydrogen maser data. The performance of the SCM is clearly superior to that of the hydrogen maser for measuring times shorter than about 30 sec, and superior to that of the SCSO for times longer than about 200 sec. SCM performance can be well characterized for times longer than 30 sec because of the overlap of the two data sets and the well-characterized hydrogen maser stability, both of which are shown in Fig. 3. However, only the test with the SCSO reference provides detailed information about SCM performance at times shorter than 30 sec, and so the contributions of the SCM and SCSO cannot be absolutely distinguished for short times. In previous tests of several SCSO sources, an increase in Allan deviation at short measuring times was reported; the Allan deviation reached a value of $1 \cdot 10^{-14}$ at 1 sec [6]. This SCSO variability is sufficient to explain the slope in the data for times less than about 5 sec, as shown in Fig. 2.

Figure 3 shows SCM stability inferred from the two sets of data shown in Fig. 2. Stability for a single hydrogen maser is also shown. A conservative estimate of SCM stability was made for short times during which equal contributions were made by the two cryogenic sources. If the slope at the shortest times is due to the SCSO, as discussed above, SCM performance would be 4–5 $\cdot$ 10^{-15} for all times from 1 to 1000 sec.

Figure 4 shows the phase noise of two signals at 8.1 GHz that were derived from the cryogenic oscillators. A value of -80 dB/f^3 was measured, which is 25 dB better than the value obtained from the newly upgraded hydrogen maser and is 20 dB better than the value reported for the best quartz-crystal oscillator.

In order to combine the short-term stability of the SCM with the long-term stability of the hydrogen maser, the SCM has been modified to allow its frequency to be tuned. A coil has been installed on the ruby housing to allow the bias field to be adjusted; this adjustment tunes the frequency of oscillation to the passband of the high-Q resonator. This coil, with 60 turns, gives a sensitivity of $7 \cdot 10^{-12}$ per mA and a range of approximately 10^{-10}. This range is sufficient to accommodate the typical SCM drift of $4 \cdot 10^{-13}$/day that occurs during long-term operation.

IV. Conclusions

For all time intervals from 1 to 1000 sec, a frequency stability in the range of 10^{15} has been demonstrated for the SCM. The measured stability of $8 \cdot 10^{-15}$ at 1 sec is 10 times better than that of the hydrogen maser for the same measuring time, and improvement over the hydrogen maser is shown for all times from 1 to 30 sec. These results appear to be better than those obtained from any rf or microwave frequency source.

Ultrastable frequency sources like the SCM will make possible new, highly sensitive experiments. An experiment in gravitational wave search is now planned with the SCM; it is being done to support gravitational wave search by the Galileo spacecraft. Furthermore, the SCM can be used to unambiguously characterize the performance of other stable sources of reference frequency, such as the hydrogen maser, for short measuring times.

A frequency pulling coil has been implemented and tested to enable the SCM to be slaved to a hydrogen maser. This combination would make it possible to combine the long-term performance of the hydrogen maser with the newly available short-term performance of the SCM.

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References

[1] S. Thakoor, D. M. Strayer, G. J. Dick, and J. E. Mercereau, "A Lead-on-Sapphire Superconducting Cavity of Superior Quality," *Journal of Applied Physics*, vol. 59, no. 3, pp. 854–858, February 1, 1986.

[2] G. J. Dick and D. M. Strayer, "Development of the Superconducting Cavity Maser as a Stable Frequency Source," *Proceedings of the 38th Annual Frequency Control Symposium*, Philadelphia, Pennsylvania, pp. 435–446, May 29–June 1, 1984.

[3] D. M. Strayer and G. J. Dick, "The Superconducting Cavity Maser Oscillator—Toward Higher Stability," *Proceedings of the Eighteenth Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting*, Naval Research Laboratory, Washington, D.C., pp. 601–610, December 2–4, 1986.

[4] R. T. Wang, G. J. Dick, and D. M. Strayer, "Operational Parameters for the Superconducting Cavity Maser," *TDA Progress Report 42-97*, vol. January–March 1989, Jet Propulsion Laboratory, Pasadena, California, pp. 64–71, May 15, 1989.

[5] S. R. Stein and J. P. Turneaure, "The Development of the Superconducting Cavity Stabilized Oscillator," *Proceedings of the 27th Annual Frequency Control Symposium*, Cherry Hill, New Jersey, pp. 414–420, June 12–14, 1973.

[6] S. R. Stein, "Space Applications of Superconductivity: Resonators for High Stability Oscillator and Other Applications," *Cryogenics*, vol. 22, no. 7, pp. 363–371, July 1980.

[7] A. J. Giles, S. K. Jones, D. G. Blair, and M. J. Buckingham, "A High Stability Microwave Oscillator Based on a Sapphire Loaded Superconducting Cavity," *Proceedings of the 43rd Annual Frequency Control Symposium*, Denver, Colorado, pp. 89–93, May 31–June 2, 1989.

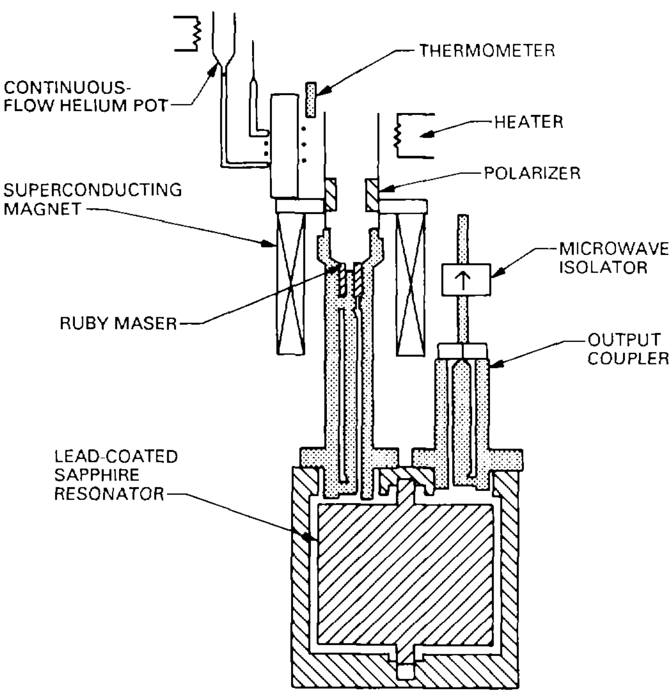

Fig. 1. The superconducting cavity maser oscillator with an improved temperature-control system. Recent modifications include consolidation of heating and cooling elements to prevent thermal-regulation power from flowing through the oscillator assembly. A direct-output coupler and microwave isolator were installed to reduce noise and increase stability. The cryogenic polarizer was added to provide effective and reproducible ruby pumping.

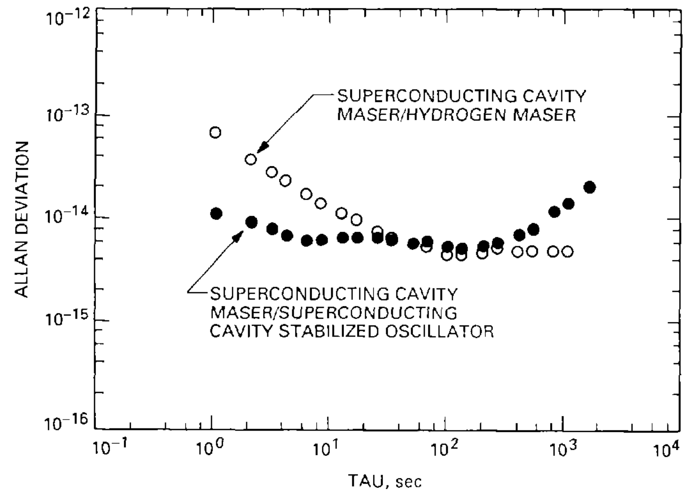

Fig. 2. Two sample Allan deviation plots of the SCM, gained by testing it with SCSO and hydrogen maser references.

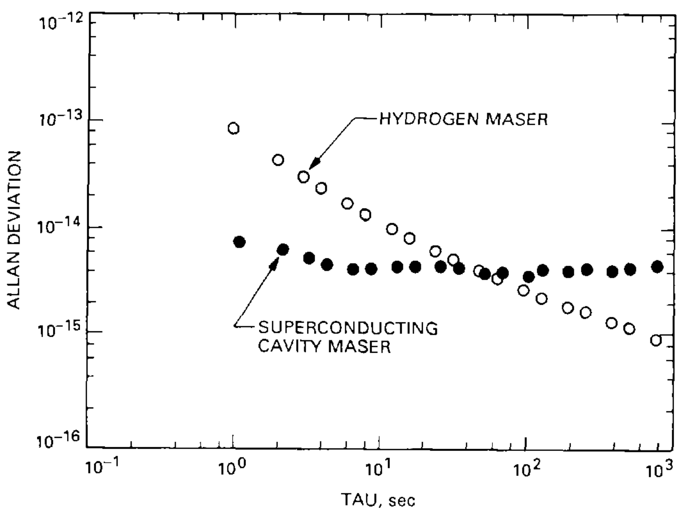

Fig. 3. Plot of the Allan deviation showing SCM stability after modifications to the SCM; also shown is the stability of a single hydrogen maser reference. Improvement over the hydrogen maser is apparent for times from 1 to 30 sec.

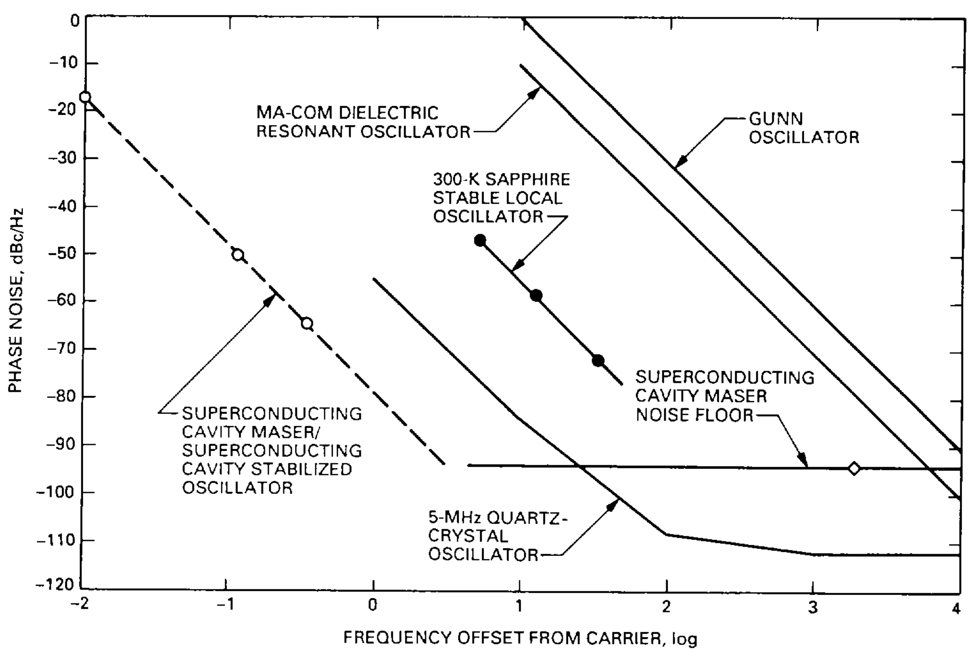

Fig. 4. Phase-noise measurements of the SCM operating at 8.1 GHz show an improvement of 20 dB over the best multiplied 5-MHz quartz-crystal oscillator performance available at 10 GHz (X-band). Noise plots for various conventional 10-GHz frequency sources are also shown.