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IMPROVED PERFORMANCE OF THE SUPERCONDUCTING CAVITY MASER AT SHORT MEASURING TIMES*

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Abstract

Recent measurements on the superconducting cavity maser (SCM) oscillator show frequency stability of parts in 10^{15} for times from 1 second to 1000 seconds. Phase noise of approximately $-80dB/f^3$ was also measured. We believe this short– and mid–term performance to be better than that of any known microwave oscillator. In particular, measured stability at 1 second interval is 10 times better than that of a hydrogen maser, and phase noise at 8 GHz is more than 20 dB below that of the best multiplied quartz crystal oscillators.

Introduction

The superconducting cavity maser (SCM) is a helium cooled, all-cryogenic oscillator with superior stability at short measuring times[1,2,3,4]. It differs from other superconducting cavity stabilized oscillator (SCSO) designs[5,6,7] in its use of a very rigid ($Q \approx 10^9$) sapphire–filled stabilizing cavity, and in its all–cryogenic design; excitation being provided by an ultra-low noise cryogenic ruby maser.

A comparison of ultra-stable atomic frequency sources shows active hydrogen masers to be superior to passive atomic standards in short term stability (1 second $< \tau <$ 100 seconds). Performance of the SCM at short measuring times is superior even to the active hydrogen maser. Like the hydrogen maser, the SCM is also an active oscillator. The advantage of the SCM is its larger output signal power ($\approx 10^{-9}$Watt vs $\approx 10^{-12}$Watt for the hydrogen maser). Long term performance is limited by variation of the operating parameters, such as temperature, drive power, output VSWR etc., depending on the sensitivity of the SCM to these various parameters.

Figure 1 shows a block diagram of the improved oscillator. The three cavity oscillator, consisting of a ruby maser, coupling cavity, and a high–Q lead–on–sapphire cavity, have been discussed previously[2]. Oscillation at a frequency of 2.69 GHz results from ruby maser operation with a 13.1 GHz pump frequency to create a population inversion. Energy level splittings in the Ruby are matched to that of the high–Q cavity by means of a bias field provided by a superconducting solenoid. Frequencies of the three modes of the coupled cavity system are spaced relatively close to each other (5% spacing) in order to couple effectively, but are spaced far enough from each other to allow mode selection by adjustment of the bias field[2].

Experimental Aspects

Substantial technical improvements have been made to eliminate frequency instability due to operational parameters. They are temperature, pump frequency, pump power, pump frequency polarization, temperature gradient, coupling strength and output VSWR. We have either stabilized the parameter or minimized the coefficient which couples the parameter to the operating frequency.

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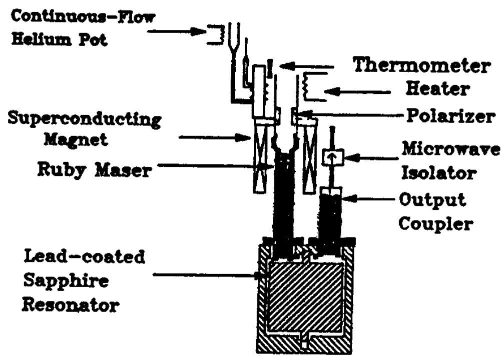

Figure 1: Schematic diagrams of the Superconducting Cavity Maser (SCM) oscillator with improved temperature control system. Recent modifications include consolidation of heating and cooling elements to prevent thermal regulation power from flowing through the oscillator assembly. A direct output coupler and microwave isolator were installed to reduce noise and increase stability. The cryogenic polarizer was added to provide effective and reproducible ruby pumping.

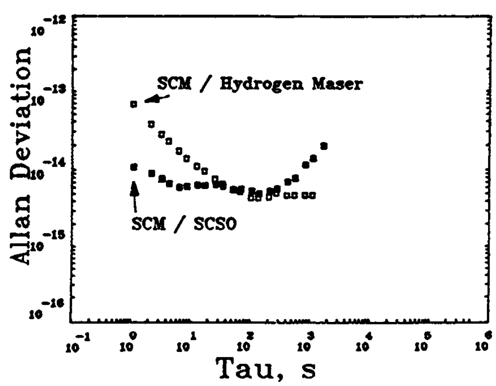

Figure 2: Two sample Allan Deviation of the SCM tested with SCSO and hydrogen maser references. Filled squares show data of SCM/SCSO; open squares are SCM/Hydrogen Maser data.

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

Frequency dependence on microwave pump frequency and amplitude has also been studied[4]. Since the pump power 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 $\leq 2 \cdot 10^{-13}/\text{db}$, a value 100 times smaller than was typically found.

Several recent improvements have made increased stability possible. They are listed as following:

1. Extension of operational period: The 1.57 Kelvin cooling system was changed from closed bath refrigeration to continuous flow. The operational period was extended from 3 days to 7 days, limited only by the storage time of the larger 4.2 Kelvin helium bath from which the small flow is drawn. We expect to extend this to 30 days with a better dewar. This modification also provides continuous operation of the SCM during helium transfer.

2. Improved temperature stability: Temperature fluctuation has been minimized to 40 microKelvins, a factor of 1000 improvement. Previously we measured a parabolic curve of oscillation frequency versus temperature with a frequency maximum near 1.57 Kelvin. With present temperature control capacity, even a temperature offset of 100 milliKelvins would only degrade the frequency stability to $4 \cdot 10^{-14}$. We are able to operate in the region of nominally zero temperature coefficient with a temperature accuracy of one milliKelvin.

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

4. More effective ruby pumping: A fixed rectangular waveguide was installed with pump signal 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 for vacuum seal and allowing low loss microwave propagation. It is expected that less pump power will be required to obtain oscillation since the un–matched impedance caused by the right angle feed will be eliminated.

6. Reduction of in-oscillator noise due to back–coupling from the room-temperature amplifier: We have installed a cryogenic isolator[8], to prevent room-temperature radiation from coupling into the oscillator and also to reduce sensitivity of the operational frequency to output VSWR.

Measurements

The improvements discussed above have made possible excellent stability at both relatively long (10000 seconds) and very short (1 second) measuring times. In order to characterize performance of the SCM at shorter times, we obtained the use of another cryogenic oscillator (SCSO) for use as a frequency reference [5,6]. Substantial improvement in other instrumentation was also necessary. New procedures included bypassing the receiver of the SCSO in order to make direct measurements between microwave frequency signals. Long term measurements primarily made use of a Hydrogen maser as frequency reference.

Figure 2 shows raw data for two tests of the SCM against SCSO and Hydrogen Maser references. The filled squares represents data of the SCM/SCSO test and open squares the SCM/Hydrogen–Maser data. Performance of the SCM is clearly superior to hydrogen maser for measuring times shorter than about 30 seconds, and superior to that of the SCSO for times longer than about 200 seconds. SCM performance can be well characterized for times longer than 30 seconds due to overlap of the two data sets and the well–characterized hydrogen maser stability as shown in Figure 3. However, only the test with the SCSO reference provides detailed information about SCM performance at times shorter than 30 seconds and so the contributions of the two sources cannot be absolutely distinguished for short times. In previous tests of several SCSO sources, a slope at short measuring times was reported, reaching a value of $1 \cdot 10^{-14}$ at 1 second[6]. This SCSO variability is sufficient to explain the slope in our data for times less than about 5 seconds as shown in Figure 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 was made for short times of equal contributions 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 second to 1000 seconds.

In a three corner hat measuring scheme, using the SCSO and a hydrogen maser as references, performance of SCM was shown to be better than hydrogen maser for all times shorter than 70 seconds with long term performance better than the SCSO.

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

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

Conclusions

We have demonstrated a frequency stability of parts in 10^{15} for all times from 1 to 1000 seconds for the SCM. The measured stability of $8 \cdot 10^{-15}$ at 1 second is 10 times better than the hydrogen maser at the same measuring time, and improvement over the hydrogen maser is shown for all times from 1 to 30 seconds. We believe these results to be better than any known RF or microwave frequency source.

Ultra-stable frequency sources like the SCM will make possible new experiments with high sensitivity. An experiment on gravitational wave search is now planned in 1992 with two SCM units to perform a "three–way" experiment with Galileo spacecraft. Furthermore, the SCM can be used to unam-

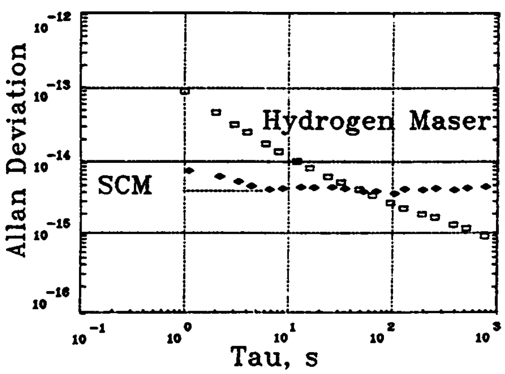

Figure 3: Plot of Allan Deviation of SCM stability after modification, also shown is stability of a single hydrogen maser reference. Improvement over the hydrogen maser is apparent for times from 1 to 30 seconds.

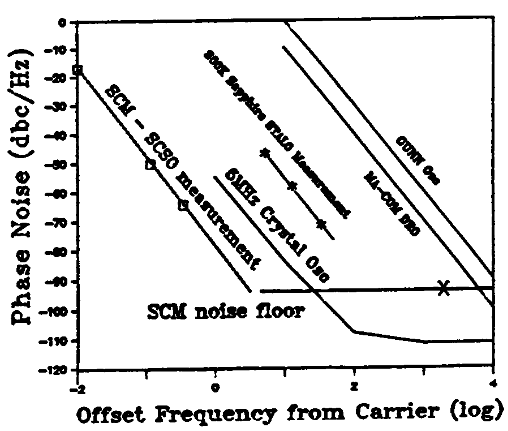

Figure 4: Phase noise measurements of SCM at 8.1 GHz show improvement of 20dB over the best multiplied 5 MHz crystal oscillator performance available at X-band. Noise plot for various conventional X-band frequency sources are also shown.

biguously characterize the performance of a 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 possible the excellent long term performance of the hydrogen maser combined with the newly available short term performance of the SCM.

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