ELSEVIER

Physica B 280 (2000) 557–558

PHYSICA B

www.elsevier.com/locate/physb

Superconducting-cavity-stabilized oscillators (SCSO) for precise frequency measurements

N.-C. Yeh[a,*], D.M. Strayer[b], V.L. Anderson[a], N. Asplund[a]

[a]Department of Physics, California Institute of Technology, Pasadena, CA 91125, USA
[b]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA

Abstract

We report our progress in achieving precise frequency measurements by integrating high-Q superconducting-cavity-stabilized oscillators (SCSO) with high-resolution thermometry and phase-locked-loop (PLL) techniques. The relevant effects that influence the ultimate frequency stability of SCSO (10^{-17}–10^{-18}) are described, and applications of this technique to precise measurements of the liquid helium critical phenomena are discussed. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Cavity stabilized oscillators; SCSO; Precise frequency measurements

Since the 1970s, superconducting-cavity-stabilized oscillators (SCSOs) have been known to provide the best frequency stability [1] ($\sim 3\times 10^{-16}$) for measurement times up to $\sim 10^3$ s. Recent advances in microwave technology and high-resolution thermometry [2,3] have projected further improvement in the frequency stability to better than 10^{-17}–10^{-18} [3–5], provided that the following stringent technical requirements are satisfied: (1) *high-quality factor* (Q) *of the superconducting cavity* – to minimize energy losses for long-term stability; (2) *high-resolution temperature control* – to minimize the temperature-dependent frequency drift; (3) *high-resolution frequency readout and control* – to provide active feedback mechanism for frequency stability; (4) *vibration isolation* – to prevent accelerations and external mechanical agitation that distort the dimensions and the frequency stability of the cavity.

We choose niobium as the superconducting material because of its relatively large superconducting energy gap and mechanical rigidity [4,5]. To minimize the residual losses of the superconducting cavity, we use chemical etching together with high-temperature ($\geqslant 1500°$C) and ultra-high vacuum ($\sim 10^{-9}$ Torr) annealing to process the cavities [6], and then measured the quality factor of the TE_{011} mode at ~ 14.12 GHz. Steady improvement of the Q values have been found with increasing annealing time, and $Q > \sim 10^{10}$ may be achieved with sufficiently long time annealing [7]. A representative set of data for one of the niobium cavities is shown in Fig. 1. More details of the cavity processing procedure and Q measurements are given elsewhere [6,7].

We have shown previously [4,5] that for operation temperatures near 2 K, the temperature-dependent frequency stability for $\omega \sim 2\pi \times 10^{10}\ \mathrm{s}^{-1}$ is $(1/\omega)(\partial\omega/\partial T) \approx -10^{-8}\ \mathrm{K}^{-1}$. Hence, the temperature stability must be better than 10^{-9} K to achieve a frequency stability in the order of 10^{-17}–10^{-18}. This can be readily achieved by using HRT [2,3]. The approach is based on high-resolution measurements of the magnetic susceptibility $\chi(T)$ of a paramagnetic salt pill using a SQUID [7]. In contrast to the early HRT which utilized RF-SQUID technique [2,3], we integrated DC-SQUID into our HRT setup, and found reduction in the voltage noise and therefore improved temperature resolution by about one order of magnitude, to $\sim 10^{-11}$ K at ~ 2 K, as shown in Fig. 2 and detailed in Ref. [7] for our HRT system. We note that the resolution is proportional to the sensitivity of $\chi(T)$, so that the data resemble $\chi(T)$ of CAB, with maximum sensitivity at $T_C \sim 1.78$ K.

To measure and stabilize the resonant frequency of a superconducting cavity to high resolution, a phase-locked loop (PLL) technique is employed. The

---

* Corresponding author.
E-mail address: ncyeh@caltech.edu (N.-C. Yeh)

0921-4526/00/$ - see front matter © 2000 Elsevier Science B.V. All rights reserved.
PII: S0921-4526(99)01863-3

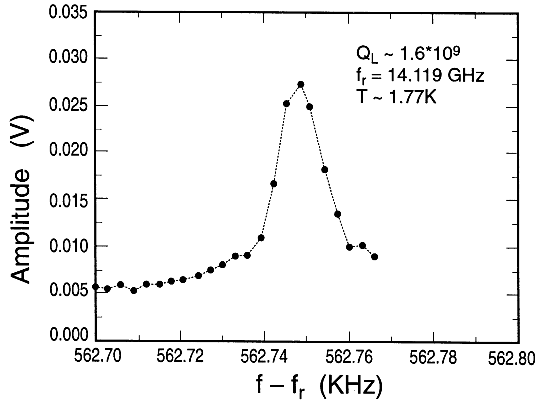

Fig. 1. Characterization of one of the cavities annealed for 20 h, showing a quality factor $Q \sim 2 \times 10^9$ at 1.77 K.

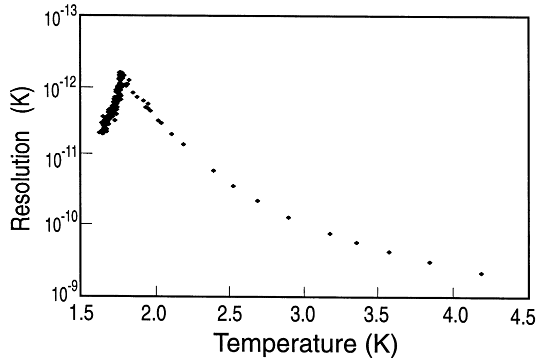

Fig. 2. The temperature resolution of our HRT system as a function of the sample temperature, using the ammonium bromide (CAB) paramagnetic salt, and calibrated with a known germanium resistive temperature sensor.

principle is to compare the resonant frequency f_0 of the superconducting cavity with the signal output of a low-noise synthesizer at a carrier frequency f_c. By using the error voltage $V_{\mathrm{err}} \propto (f_c - f_0)$ in an active feedback circuit to tune the frequency of the low-noise synthesizer, the frequency f_0 may be read and stabilized to high resolution ($\sim 10^{-7}/Q$) [6,7]. The block diagram of the system is depicted in Fig. 3. We emphasize the necessity of using a very stable frequency standard as a comparison source in the readout. The next step for us is to acquire a cesium standard with $\sim 10^{-14}$ frequency stability for comparison, and later to construct a second SCCO for even better resolution.

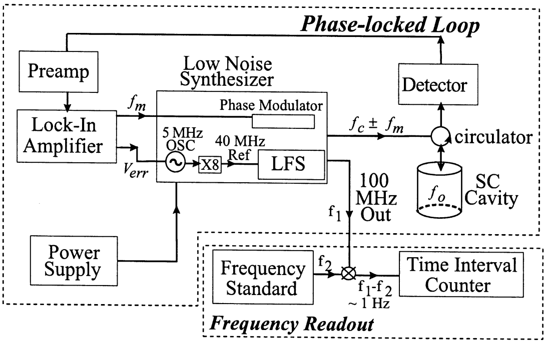

Fig. 3. The block diagram of the frequency control and readout system. (LFS: low-noise frequency synthesizer).

In addition to the obvious application as frequency standards, the SCSO system may be applied to perform precise measurements of the critical phenomena of liquid helium near phase transitions by determining the temperature-dependent dielectric constant from the resonant frequency shift of a Nb cavity that contains liquid helium [4,5]. Hence, the SCSO system is versatile, not only as the best short-term frequency standard, but also as a vehicle for verifying the fundamentals of renormalization group theory.

Acknowledgements

This work is supported by NASA.

References

[1] S.R. Stein, J.P. Turneaure, Proc. IEEE 63 (1975) 1249.
[2] J.A. Lipa et al., Physica 107B (1981) 331.
[3] H.Y. Fu et al., J. Low Temp. Phys. 111 (1998) 49.
[4] N.-C. Yeh et al., J. Jpn. Microgravity Appl. 15 (Suppl.) II (1998) 136.
[5] N.-C. Yeh et al., Czech. J. Phys. 46 (Suppl.) S1 (1996) 181.
[6] W. Jiang et al., J. Jpn. Microgravity Appl. 15 (Suppl.) II (1998) 157.
[7] N.-C. Yeh, D.M. Strayer, Int. J. Mod. Phys., 1999, to appear.