SUPERCONDUCTING STRIPLINE RESONATORS AND HIGH-T_c MATERIALS*

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ABSTRACT

The use of high-transition-temperature (T_c) superconducting resonators to stabilize oscillators operating between 1 and 10 GHz is discussed. Measurements of surface resistance are presented and related to resonator quality factor (Q). Projections of resonator Q and oscillator phase noise are discussed. Improved materials should offer greater than 20 dB reduction in noise over competing technology. The implications of flicker noise in reaching this level of performance are discussed, and preliminary measurements of flicker noise in the high-T_c materials are reported.

I. INTRODUCTION

The discovery of the high-T_c superconducting materials has stimulated interest in many applications, one of which is resonators for the stabilization of low-phase-noise oscillators which could be operated at liquid nitrogen temperatures (77 K). The ability of present day Doppler radar systems to detect small-cross-section targets in the presence of clutter is limited by the phase noise in the local oscillator. A reduction of 10 to 20 dB would increase the sensitivity a corresponding amount. Superconducting resonators hold the promise of providing such improvement because they are known to have high Q and high power-handling capability, both of which lead directly to lower phase noise. Qs of 10^6 for thin-film stripline resonators operating at 1 GHz and 10^5 at 10 GHz with a power handling capacity of greater than 1 W are achievable with niobium at liquid helium temperatures. Better performance than niobium is expected for the high-T_c materials at liquid nitrogen temperatures. Cavity resonators have demonstrated Qs higher than the stripline values, but because of the difficulties in fabricating the three-dimensional cavity structure, especially in the high-T_c oxide materials, the stripline structure is preferable for most applications. Stripline eliminates the radiation losses of microstrip and it has the advantage of planar fabrication techniques; the coupling and resonant frequency are determined photolithographically and the structure can be made compact and environmentally rugged.

The resonator Q is determined by the radio-frequency (rf) surface resistance R_s of the superconducting material which, although low, is not identically zero as it is at dc(1). At any ac frequency and finite temperature, resistive losses are present because the kinetic inductance of the superconducting electrons causes a coupling of the field to the normal electrons with their associated dissipation. Thus a superconducting material is characterized by a surface resistance that typically increases as frequency squared. This loss can become appreciable at microwave and millimeterwave frequencies and can severely limit the Q of a resonator. The measurements of the rf surface resistance which have been made to date show that R_s is very dependent on film fabrication. As discussed below, our estimates of resonator Q presently rely upon measured surface resistance. The best reported values of R_s are more than ten times better than copper at 1-10 GHz and 77 K and projections based on a simple two-fluid model indicate that there is still considerable room for improvement in R_s.

High input power is also required which translates into high critical current (J_c) values. Presently, in the high-T_c materials, both surface resistance and critical current are orders of magnitude better in thin films than in bulk ceramic materials, dictating the use of thin films to meet the low-phase-noise requirements. We thus concentrate on the properties of deposited thin film materials.

In the following we summarize the measurements of surface resistance and then show how R_s is used to calculate resonator Q. Detailed calculations of oscillator phase noise will be presented, including such factors as amplifier flicker noise and power-handling capability of the superconductor.

II. MEASUREMENTS OF R_s

The surface resistance of the oxide superconductors has been measured by our group at Lincoln Laboratory in $YBa_2Cu_3O_x$ (YBCO)(2) and more recently in $Bi_2Sr_2CaCu_2O_x$ (BSCCO). The measurements are made using the stripline resonator structure shown in Fig 1. The resonator comprises a length of transmission line one-half wavelength long at the fundamental frequency and two ground planes above and below the line. Overtone resonances occur at all multiples of the fundamental frequency. The resonator is capacitively coupled to the external circuit by gaps in the stripline. The structure is made from niobium deposited on sapphire substrates, but to evaluate R_s of a new film the niobium bottom ground plane is replaced with a film of the material to be tested. The dielectric properties of the substrate of the test film do not affect the resonator properties. We can ignore the contribution of the niobium because, currently, the R_s of the test film is large compared to that of the niobium.

The resonator Q is measured as a function of frequency between 0.5 and 18 GHz, and R_s is extracted from the Q measurements as described in Section IV.

Other measurements of R_s have been done, notably by groups at UCLA(3), the University of Wuppertal(4), and Rockwell(5). Figure 2 shows a collection of measurements of R_s at various frequencies. The Lincoln Laboratory measurements on YBCO show a T_c of about 85 K but surface resistance several orders of magnitude larger than that of the best reported films. The lowest values of surface resistance have been obtained by the Wuppertal(4) group for oriented thin films of YBCuO deposited on $SrTiO_3$ by laser ablation. The reported R_s values measured at 77 K and 86 GHz are more than an order of magnitude lower than that of copper. Extrapolation to frequencies lower than 10 GHz implies an R_s more than 100 times better than copper. These best yet values of R_s are used later in Section IV to estimate potential resonator Qs.

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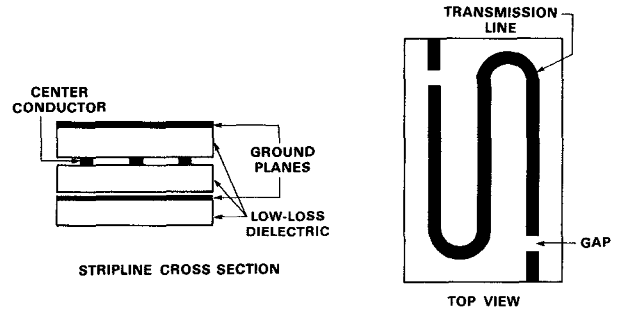

Fig. 1. Schematic view of the stripline resonator. On the left is a cross section showing dielectrics and conductors. On the right is a top view of the center section showing the center conductor which has been patterned photolithographicaly. The gap shown determines the coupling to the resonant section of line.

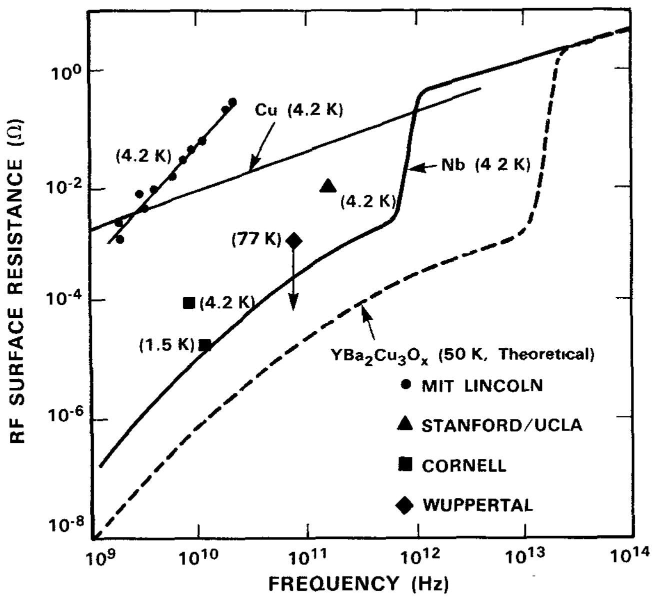

Fig.2. Various measurements of RF surface resistance R_s vs frequency. Also shown are calculations for copper and niobium at 4.2 K and the result of two-fluid-model estimate for $YBa_2Cu_3O_{7-X}$ at 50 K.

III. DIELECTRIC MATERIAL CONSIDERATIONS

In addition to low-rf-loss thin films, low-dielectric-loss substrates compatible with the thin-film-deposition process must also be employed. The Q of a resonator results from several contributions. Thus,

$$Q_L^{-1} = Q_{ex}^{-1} + Q_C^{-1} + Q_D^{-1} \quad (1)$$

where Q_L is the loaded Q, Q_{ex} represents the loading of the resonator and can be adjusted by varying the coupling to the external circuit, Q_C reflects the conductor loss and is inversely proportional to the rf surface resistance of the conductors, and Q_D results from losses in the dielectric and is related to the loss tangent (tan δ) by

$$Q_D = 1/\tan\delta. \quad (2)$$

As can be seen from expressions (1) and (2), tan δ lower than 2×10^{-6} is necessary to achieve Qs larger than 500,000.

The stripline resonator structure shown in Fig. 1 can also be used to measure loss tangents at 4.2 K by replacing the sapphire top ground plane with one of the materials to be tested on which a niobium film has been deposited. Measurements of the dielectric loss at 4.2 K of single crystals of MgO have been performed in our laboratory and imply a tan δ of better than 1.2×10^{-6} at 500 MHz and 4.2 K. Also, our preliminary measurements on $LaGaO_3$ show a tan δ of 2×10^{-6} at 500 MHz and 4.2 K. These values are adequate for high-Q resonators at 4.2 K and we are investigating tan δ at higher temperatures.

IV. PREDICTIONS OF PHASE NOISE

In this section we analyze an oscillator stabilized by a stripline resonator. To calculate the phase noise of such an oscillator, we must estimate the Q expected for the stripline structure and the maximum oscillator power which the resonator can support. As will be shown later, high values of both are desired for low phase noise. The detailed method will be published elsewhere(6) and we just quote the results here. The attenuation constant α_c for our stripline geometry is given by

$$\alpha_c = 6.87\ R_s.$$

We can than relate Q_c to α by

$$Q_C = \frac{\pi}{\alpha_C \lambda} \quad (3)$$

where λ is the wavelength in the resonator.

The high Qs and high input power necessary for low phase noise in the oscillators translate into very high current densities for the conductors. The maximum power is that power for which the critical current density J_c is not exceeded. To calculate the maximum allowable power incident on the resonator, we consider the currents flowing at resonance and derive the result,

$$P_C = \frac{n\pi R_L I_{max}^2}{8IL(1-IL)} Q$$

where R_L is the load resistor I_{max} is the critical current and IL is the resonator insertion loss (fractional power transmitted).

To calculate the Q, we assume $R_s = 2.7 \times 10^{-5}\ \Omega$ at 5 GHz and 77 K. This value of R_s is obtained by extrapolating the results from the Wuppertal measurements of oriented YBCO deposited on $SrTiO_3$, done at 87 GHz, to lower frequencies by assuming that R_s is proportional to f^2, which is expected on theoretical grounds and has been observed for most measurements of the high-T_c films. To calculate P, we assume a critical current density of 5×10^6 A/cm^2 at 77 K. Values of critical current density of approximately this magnitude have been reported by several groups. For these values, and assuming an insertion loss of 15 dB, we obtain an unloaded Q of 7.3×10^5 at 5 GHz and a maximum input power of 0.83 W. From the standard Leeson model of the phase noise of a feedback oscillator(7), the single-sideband noise is given by

$$L(f) = 10 \log\left[N^2\left(1 + \frac{f_0^2}{4Q^2f^2}\right) \bullet \left(\frac{\alpha}{2\pi f} + \frac{GFkT}{P_c}\right)\right]$$

where L(f) is in dBc/Hz, P_c is the oscillator power, G the loop gain, F the amplifier noise figure, f the offset frequency in Hz, Q the resonator quality factor, f_o the oscillator frequency, α the flicker-noise constant which must be empirically determined from the 1/f measurements, T the absolute temperature, k is Boltzmann's constant and N the frequency-multiplication factor.

The flicker (1/f) noise can originate in either the amplifier or the resonator or both. Since the flicker noise is not well understood theoretically, it must be empirically determined. We can make reasonable estimates for the amplifier, but for the resonator we must rely on experimentally determined values. Our projections of phase noise that follow assume that the contribution of the resonator to the flicker noise is small compared to the amplifier contribution, but the total phase noise at offsets of less than about 5 kHz is dominated by the flicker noise. If the flicker noise contribution of the superconducting resonator is larger than that of the amplifier, then the actual phase noise will be greater than the following predictions. The importance of the resonator flicker noise has led us to undertake the measurements described in Sec. V.

Figure 3 shows the projected phase noise at 10 GHz for a superconducting-resonator-stabilized oscillator operating at 5 GHz, frequency-doubled to obtain 10 GHz. The parameters are Q of 7.3×10^5, G of 18 dB, F of 3 dB, P_c of +27 dBm (0.5 W), and α of 4×10^{-12}. This value of α is that normally assumed for a GaAs FET amplifier. The parameter values chosen for these curves are the best currently available but should not be considered final because improvements in R_s would result in higher Qs. We have, for instance, assumed room-temperature operation for the amplifier, but when the amplifier is operated at the cryogenic temperatures, noise performance would be improved. Also shown in Fig. 4 are the phase-noise curves for SAW oscillators(8) and for quartz crystal oscillators.(9) Clearly the superconducting oscillator provides better performance than other technologies.

V. RESIDUAL NOISE MEASUREMENTS

Because of the importance of 1/f noise and because no measurements are known to us, we have made a series of measurements using the stripline structure shown in Fig. 1. The substrates for these devices are silicon (p-type, 30 Ω-cm) and the conductors are deposited niobium. The gap in the stripline determines the coupling of the resonator to the external circuit and thus affects Q_L, the loaded Q, which can be varied by changing the size of the gap in the line. The fundamental resonant frequency of these devices is 1.1 GHz. The gap size has been varied from 150 µm to 500 µm. This range of gap sizes gives a Q_L which varies from 23,000 to 300,000. The largest Q_L is very close to the intrinsic Q for the niobium-on-silicon resonators. Table 1 summarizes the devices used in the measurements.

Table 1.

Gap µm	Q_L	L(f = Hz) dBc/Hz
150	23,000	-120
300	80,000	-110
400	200,000	-100
500	250,000	- 95

Measurements of the residual noise are shown in Fig. 4. Plotted is the single-sideband phase noise L(f) in dBc/Hz as a function of the offset frequency from the carrier for each of the devices measured. The data exhibits the expected behavior for a resonator, namely, a flat region dominated by the system noise floor at large offset frequencies joined to region of 1/f slope at small offset frequencies extending to less than 1 Hz. As can be seen from the data, the noise increases with increasing Q_L. The 1/f noise is often characterized by the value of the noise at 1 Hz offset from the carrier. This parameter, L(f=1 Hz), is shown in Table 1.

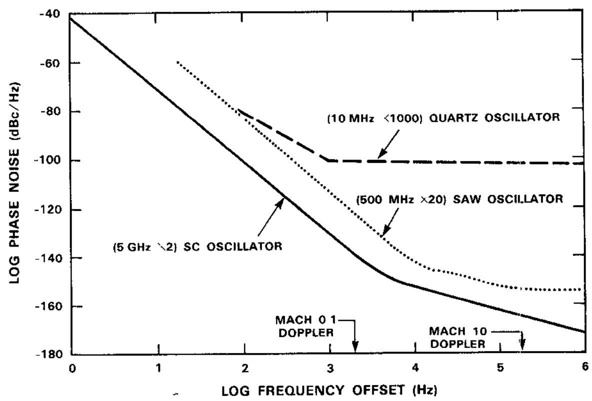

Fig. 3. Projected value of the single-sideband phase noise at 10 GHz for an oscillator stabilized with a superconducting resonator. See text for the detailed parameters of the oscillator. Also shown are the phase noise for the best SAW oscillator and a production quartz crystal oscillator.

A useful model of 1/f noise in acoustic resonators has been developed(10) which assumes that the source of the 1/f noise is fluctuations of the center frequency of the resonator which have a 1/f frequency distribution. Since the slope of $\phi(f)$, the transmitted phase, is proportional to Q_L, the same amplitude center frequency fluctuation should produce higher phase noise as Q_L is increased. Since L(f) is a measure of the power in the fluctuation, the 1/f noise should increase as the square of Q_L according to this model. The result agrees well with our data.

The measured 1/f noise of these niobium resonators at 1-Hz offset from the carrier is larger than the measured values for good quality surface-acoustic-wave resonators which have a value of -130 dBc/Hz at 1-Hz offset(11). The measured values are large enough to limit the performance of oscillators stabilized with these resonators. Sources of the 1/f noise, such as temperature fluctuations, vibration sensitivity, and conduction processes in the film, are being investigated.

We have also measured the 1/f noise of the resonators containing a high-T_c film as the lower ground plane. Figure 5 shows a typical example of the results obtained with a BSCCO film fabricated at Lincoln Laboratory(12) by means of sequential e-beam evaporation of the constituents on a MgO substrate. The film was annealed at 870° C in O_2 following evaporation. The BSCCO served as the lower ground plane in an otherwise all-niobium resonator. The resonator had a $Q_L = 10^4$ and was measured at the fundamental frequency of 550 MHz. The 1-Hz intercept, L(f=1 Hz) is -90 dBc. These are typical results for the high-T_c ground planes that we have measured. All films show a 1/f noise which is significantly higher than that of niobium. The origin of the 1/f noise is not well understood and may be related to the quality of the films which we have tested. We will soon measure the 1/f noise is films deposited in a manner which is known to produce lower values of R_s and we expect that the noise properties will improve.

VI. CONCLUSIONS

High-T_c materials have now advanced sufficiently that the best reported T_c, R_s and I_c indicate that high-Q microwave frequency resonators operating at 77 K can be envisioned.

Projected phase-noise performance is very good, bettering the competing technologies by a significant amount. However, the currently measured values of flicker noise are too high to reach the level of performance consistent with the other parameters. We believe that as the high-T_c superconducting film quality increases, the 1/f noise will decrease, but this parameter remains a major obstacle to application of these materials as resonators for oscillator stabilization. Additionally, further progress must be made in producing films reliably with low R_s over large areas on substrates with low tan δ.

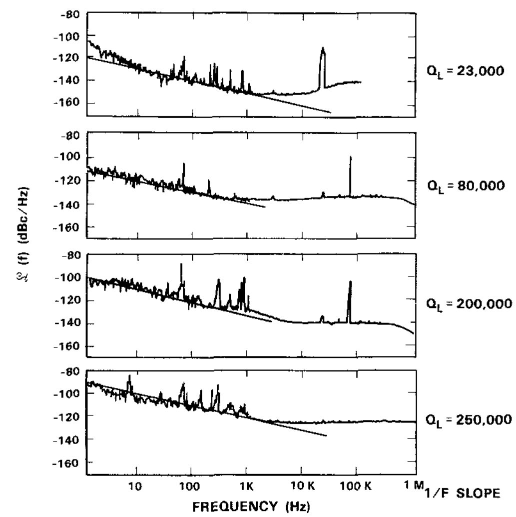

Fig. 4. Set of four residual-noise measurements in Nb resonators with the indicated values of Q_L, the loaded Q. Plotted is L(f), the single sideband phase noise, versus offset frequency from the carrier. The noise follows the expected 1/f frequency dependence. The straight lines indicate a 1/f dependence.

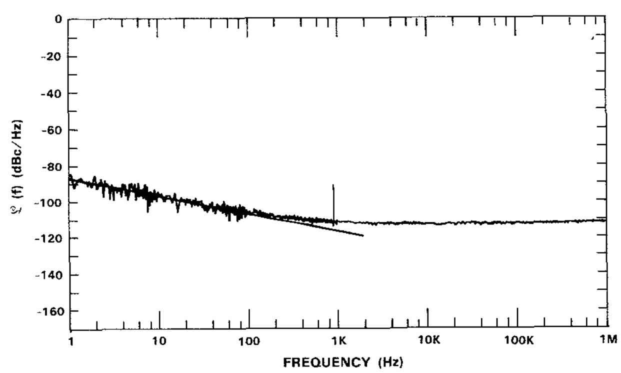

Fig. 5. Typical results of 1/f noise measurements using a resonator with one ground plane of the high-T_c material.

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