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A SUPERCONDUCTING RF NOTCH FILTER*

C. S. Pang, C. M. Falco, R. T. Kampwirth, and I. K. Schuller

Argonne National Laboratory
Argonne, Illinois

and

J. J. Hudak and T. A. Anastasio

Department of Defense
Fort Meade, Maryland

INTRODUCTION

Over the past several years major improvements have been made in the quality of high T_c A-15 superconductors. In particular, high-quality thin films of Nb_3Sn and Nb_3Ge have been fabricated using chemical vapordeposition [1], coevaporation, [2] and magnetron sputtering [3] techniques. Aside from the potential applications of these materials to ac power transmission, high-field magnets, and particle accelerators, their high transition temperatures might be exploited for use in devices cooled by closed-cycle refrigeration.

Most superconducting devices such as the various forms of Josephson junction devices, super-Schottky diodes, cavity and helical resonators, and thin-film bolometers generally require operation at liquid helium temperatures. Low operating temperatures are often necessary to reduce device noise, provide lower resistive losses, or obtain the specific superconducting properties offered by low T_c materials. The inherent disadvantage of low operating temperature is that refrigeration is typically provided by liquid helium baths which must be replenished frequently. In addition, the transfer of liquid helium from storage dewars is awkward and unacceptable to a nontechnical user. Small Joule–Thomson expansion liquefier stages added to closed-cycle refrigerators can be used in some applications, but are not readily available.

Applications that would allow use of high-quality, high T_c thin-film materials and allow operating temperatures between 9 and 15 K could take advantage of the reliable refrigeration systems which are now commercially available. A preliminary investigation is presented of a radio frequency superconducting notch filter employing thin-film technology which could be used for interference reduction in a communication system [4].

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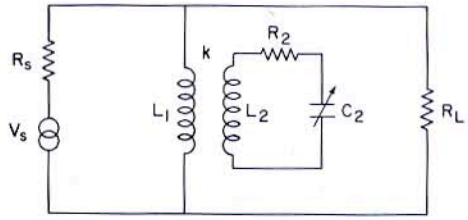

Fig. 1. Model circuit of notch filter.

CIRCUIT DESIGN

The circuit used in this investigation is shown in Fig. 1. The filter consists of an inductively coupled superconducting tank circuit which is placed in parallel with the load of the receiver, R_L. The mutual inductance between L_1 and L_2 is controlled by the coupling constant, k. The circuit is tuned by varying the capacitor C_2 and the resistive losses of the tank circuit are modeled by the series resistance R_2. For a narrow band of frequencies the filter impedance becomes very small with respect to the load, thereby reducing the strength of the interfering signal at the receiver. The maximum value of the notch depth, D, the 3-dB bandwidth of the notch, Δf, and the center frequency, f_0, at which maximum attenuation occurs, are given by [5]

$$D(\text{dB}) = -20 \log (1 + B) \tag{1}$$

$$\Delta f = \frac{1}{2\pi} \frac{Rk^2}{L_1(1-k^2)} \left[1 + \frac{2}{B} - \frac{1}{B^2} \right]^{1/2} \tag{2}$$

$$f_0 = \frac{1}{2\pi} [L_2 C_2 (1-k^2)]^{-1/2} \tag{3}$$

where $B = Rk^2 L_2 / R_2 L_1$ and $R = R_s R_L / (R_s + R_L)$.

Equation (1) shows that reducing R_2 leads to a deeper notch if the other circuit parameters are kept constant. It is also clear that the circuit has the property that the bandwidth and notch depth are independent of the center frequency. In the intended application this is a desirable feature which allows for a very large tuning range. Knowledge of L_1, L_2, D, and Δf allows one to solve for the value of R_2. Thus, the circuit can also be used to study the nature of the superconducting losses.

CIRCUIT REALIZATION

The filter circuit was implemented using the planar geometry shown in Fig. 2. The coupling constant, k, between L_1 and L_2 was controlled by the separation distance between plates A and B, and the capacitance, C_2, was controlled by the separation between plates B and C. The present design allows the superconducting tank circuit to be built without the need for any plate to plate connections, thus eliminating contact resistance as a potential source of problems.

The planar geometry was chosen so that sputtered films of high T_c Nb_3Sn or Nb_3Ge could be used. However, for these initial experiments niobium films were used for convenience. Films, about 0.5 μm in thickness, were deposited using electron beam and sputtering techniques on 5-cm-diameter single-crystal-sapphire (Al_2O_3) and fused-quartz (SiO_2) substrates. In order to obtain better adhesion between the niobium film and substrate, the latter was held at a temperature of about 300 to 400°C during the deposition process. Scanning electron microscopy showed the film surface to be smooth on the scale of 0.1 μm.

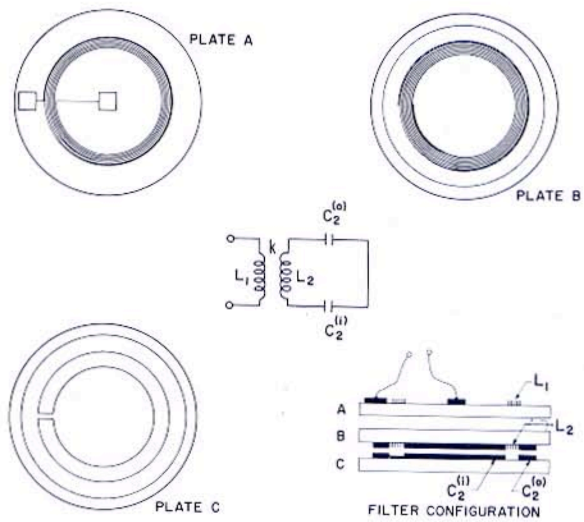

Fig. 2. Geometry of circuit elements and their relative position. (Notice the plate-to-plate connections are not required in this design.)

The circuit elements were etched into the films using photolithographic techniques. The circuit patterns for the masks were computer generated and plotted on a Gerber plotter; emulsion masks were made by photoreduction with a $\times 10$ reduction camera. Shipley AZ-1350J photoresist was spun onto the films and exposed by a mercury arc lamp using direct contact printing. The etchant used for the final development of the coil and plate patterns consisted of one part H_2SO_4, two parts HF, one part HNO_3, and four parts H_2O by volume. This etchant was found to work well on Nb_3Sn as well as on niobium [6].

The primary and secondary inductors were made with 50-μm-wide lines on 75 μm centers and had 25 and 58 turns, respectively. Each inductor had an inside diameter of 3.00 cm and an outside diameter of 3.86 cm. The values of L_1 and L_2 were calculated [7] to be 40 and 210 μH. The superconducting properties of the circuit elements made from the sputtered niobium films were obtained by standard dc measurements. The transition temperature was found to be 9.3 K and the dc critical current of the coils was about 90 mA. The typical resistivity ratio between room temperature and a temperature just above the transition temperature was about five.

RESULTS AND DISCUSSION

Measurements were carried out at 4.2 K with the circuit assembly shown in Fig. 2, immersed directly in liquid helium. Signals were transmitted into and out of the cryostat with the help of 50-Ω semirigid coaxial lines. The signal source used was an HP 606-A signal generator, and the input and output voltages were measured on an oscilloscope with a 50-Ω termination. The overall-frequency response of the filter was obtained by performing point by point measurements. For illustration purposes, a typical curve of the output to source signal ratio vs. frequency over the entire frequency range is shown in Fig. 3. This was taken with the input signal level at

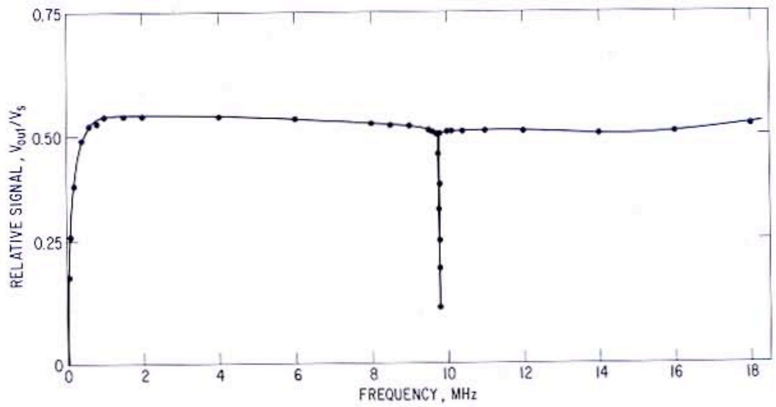

Fig. 3. Overall frequency response of filter.

40 mV. A node exists in the low-frequency range, the output signal rises rapidly with frequency and levels off at higher frequencies when the impedance of the filter circuit becomes greater than the 50-Ω load resistance. As the frequency increases further, the voltage ratio remains at about 0.5. The notch of the filter appears as a sharp dip of the output voltage. The detailed shape of a notch on an enlarged frequency scale is shown in Fig. 4.

From a series of measurements, a plot of the reciprocal of the square of the notch frequency vs. the tuning capacitance was obtained, as shown in Fig. 5. The linear dependence of $1/f_0^2$ with C_2 is in accordance with the relation in (3). From this plot the stray capacitance of L_2 and the associated capacitor plates is found to be about 3.2 pF from a straight-line extrapolation. The existence of this capacitance imposes an upper limit of 11.7 MHz on the tuning range. Furthermore, the same results allow the calculation of the actual inductance of the secondary coil, which is found to be 53 μH. It should be noted that this value is about four times smaller than the nominal inductance calculated from the geometry. In addition, from an independent experiment, by measuring the resonant frequencies of the tank circuits of a capacitor connected in series with the coils, the ratio of inductance between L_1 and L_2 was obtained to be 0.75, and the above observed value of L_2 was confirmed. The

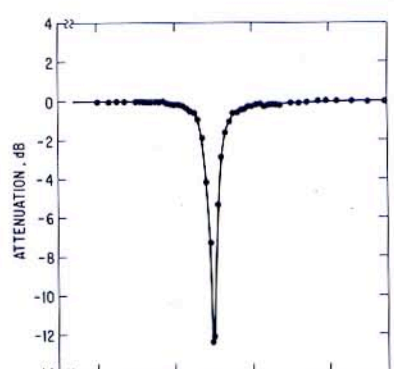

Fig. 4. Detailed shape of a typical notch.

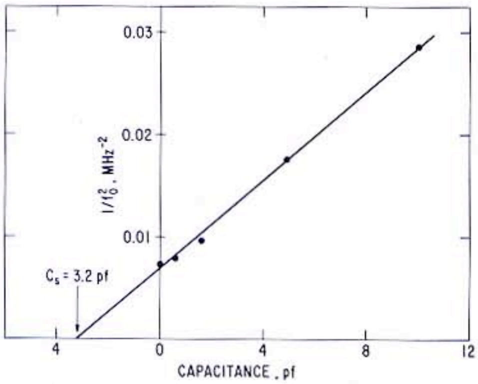

Fig. 5. Dependence of notch frequency on tank circuit capacitance.

reduction of inductance in L_2 appears to be the result of magnetic field screening produced by the superconducting plates which are located in proximity to the coil.

As shown in (1), the depth is sensitive to the resistance R_2 and the coupling coefficient k. By increasing the coupling, the maximum notch depth observed was about 17 dB for the nominal 50-Ω loading conditions. Values of k and R_2 can be calculated from the measured depth and bandwidth of the notch from (1) and (2). The values of k obtained in this fashion are smaller than theoretically predicted values [7] based upon the inductance of L_1 and L_2, and the separation of the coils. This result indicates that the presence of superconducting materials near the coils reduces the flux coupling, and that magnetic shielding has to be taken into account in a realistic calculation of the coupling coefficient. The resistance of the tank circuit obtained in this fashion is given in Fig. 6 as a function of frequency. From this graph, the resistance is found to be proportional to ω^n with n approximately equal to 1.6 over the entire frequency range.

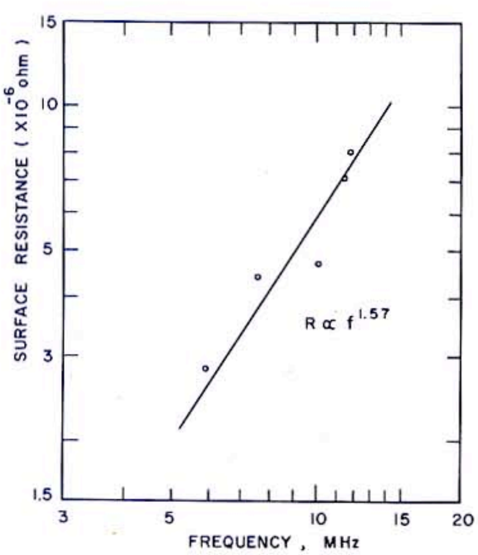

Fig. 6. Resistance of secondary coil as a function of frequency at 4.2 K.

The maximum power handling capability of the filter is about 4 mW, which corresponds to about 50 mA and 200 V of current and voltage being developed in the tank circuit. This is in reasonable agreement with critical current measurements. In the frequency range of 2 to 12 MHz, the output to source signal ratio is independent of the signal strength within the 4-mW maximum just discussed, which indicates that the resistance does not vary with the current in contrast with the results of Blair *et al.* [[8]], who find that the rf loss increases with signal levels. Finally, the quality factor Q of the present filter is about 2000 with 50-Ω source and output impedance while the circuit is fully loaded.

Theoretical calculations indicate that at temperatures below $T_c/2$ and frequencies lower than the pair-breaking frequency, the intrinsic resistance is proportional to the square of the frequency [[9]]. For real materials, however, the resistance is also determined by other material properties [[10–16]], such as (1) surface roughness and the oxide layer on the superconductor, (2) trapped magnetic vortices and normal domains in the material, (3) magnetic hysteresis effects of the flux motion, (4) losses by magnetic coupling to normal metals, and (5) dielectric loading. Recently, Judish *et al.* [[17]] measured the surface resistance of a helically loaded lead cavity at frequencies from 136 to 472 MHz. Extrapolation of their data to 10 MHz and 4.2 K yields a value of the surface resistance of about $10^{-9}\ \Omega$, which is within a factor of 20 of the measurements obtained in this study on the niobium film (normalized to the same low-temperature resistivity).

Although the dominant loss has not been identified in this case, the strong frequency dependence of the observed resistance rules out the possibility of dielectric loss in the substrate materials. Such a loss depends on the dielectric loss tangent which is only a weak function of frequency in the range of the present measurements [[18]]. Hysteresis loss can also be ruled out since this loss should depend linearly on frequency and a dependence of the loss on signal strengths has not been observed.

SUMMARY

A preliminary investigation has been conducted of a superconducting notch filter for possible application in the 2 to 30 MHz high-frequency (HF) communication band. The circuit was successfully implemented using planar geometry so that closed-cycle refrigeration could be used to cool circuits fabricated from high T_c Nb_3Sn or Nb_3Ge thin films. In the present design, circuit Q's of about 2000 were obtained with a 50-Ω source and output impedance. Circuit Q's of about 1000 to 2000 are required in order to perform filtering of signals in the HF band; the high Q's available with superconducting technology coupled with the possibility of implementing a wide tuning range outperforms conventional tunable notch filters. Conventional HF notch filters have typical circuit Q's of about 75 to 100 at 10 MHz and are typically limited to an octave tuning range. The maximum input power to the filter was found to be about 6 dBm, which enables the superconducting filter to be used to protect receiver front ends from strong HF interference signals. Measurements indicate the rf critical current is comparable to the dc critical current, thus providing a means for estimating the maximum power handling capability. The undesirable effects of magnetic flux shielding on L_2 has led to an improved design utilizing rutile (TiO_2), a low-loss and high-dielectric-constant material, to reduce the capacitor plate area. Knowledge of the resistance and its frequency dependence can be used to predict the performance of resonators at other frequencies. In this preliminary investigation the dominant source of loss has not been uniquely identified, although the results indicate that dielectric or hysteresis losses are not dominant.

ACKNOWLEDGMENTS

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DISCUSSION

Question by D. Petrac, Jet Propulsion Laboratory: How many turns does the inductor have and what are its inductance values?

Answer by author: There are 25 and 58 turns in the primary and secondary coil, respectively, with a mean diameter of about 3.4 cm. The calculated values of inductance are 40 and 210 μH.

Question by C. H. Morgan, Brookhaven National Laboratory: Did you consider geometrics other than flat spirals, e.g., coaxial coils?

Answer by author: Yes, besides the planar configuration presented here, we have also considered a geometry in which the inductors were fabricated by etching thin-film coating on a hollow dielectric cylinder.

Question by R. C. Longsworth, Air Products and Chemicals, Inc.: How was the device cooled during the experimental work?

Answer by author: In this measurement the filter assembly was immersed directly into a liquid helium bath.

Question by R. C. Longsworth, Air Products and Chemicals, Inc.: What will the closed-cycle refrigerator requirement be in terms of temperature, temperature stability, capacity, vibration, etc.?

Answer by author: It should be kept in mind that we are only in the preliminary stages of a feasibility study period. All of the details of filter performance, operation, and construction depend on the results of the study. These have not all been worked out. The goal of the first part of the study is to establish the limitations of filter performance. We have not yet measured the performance as a function of temperature. So far, the study suggested that the operating temperature of a Nb_3Sn filter should be kept below about 12 to 13 K and it is expected that performance will be insensitive to temperatures below this point.