IAN 52 APPLYING LOCK–IN AMPLIFIERS TO THE MEASUREMENT OF SUPERCONDUCTOR RESISTANCES AND T_C

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by Jim Scott

DL INSTRUMENTS, LLC

233 Cecil A. Malone Dr., Ithaca, New York 14850 Phone 607-277-8498; Fax 607-277-8499

Researchers are faced with plotting the transition from finite resistance (perhaps a few ohms) to near zero resistance (perhaps less than 10^{-3} ohms) as a function of temperature. This affords a means for measuring the critical temperature, T_c , as a function of applied current or external magnetic field.

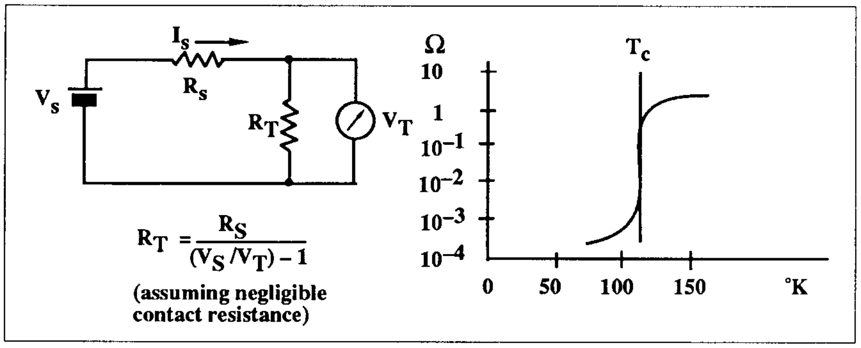

Figure 1 dc Measurement of T_c

When small currents must be used (e.g. <1 mA) the miniscule voltages dropped across the sample become very difficult to resolve from error sources such as instrumentation random input noise. Discrete frequency interferences coupled capacitively, inductively and via ground loops from the laboratory environment may also wreak havoc with the results. If a dc measurement is attempted, such as shown in Figure 1, then the thermocouple emf arising from the inevitable thermal gradients between wiring to sample connections must be dealt with. This typically would involve a somewhat slow and cumbersome technique such as polarity switching and the tracking of thermal drift rates as the sample temperature is raised or lowered. A dc method also is inherently noisy due to operation in the highest 1/F noise region of the instrumentation. A typical setup operating at 10 mA might require 2 seconds to acquire a sample with 25 micro-ohm output uncertainty.[1] The plotting of a transition curve would take several minutes, even at this relatively high current level.

Going to an ac technique as shown in Figure 2 offers a number of improvements. First, the measurement uncertainty due to instrumentation random noise can be one or two orders of magnitude lower, depending on the choice of remote preamplifier. For a given level of resistance reproducibility, this noise improvement can be traded for a significant increase in measurement rate at the same current level employed by the dc technique. Second, the narrowbanding filtering characteristic of the lock–in affords rejection of extremely high levels of discrete frequency interference (~80 dB). The multimode input signal conditioning filter of the 3961B and 3962A Lock–Ins can be very helpful in this regard. Third, thermal emf problems are entirely eliminated. Fourth, the internal low drift (~200ppm/°C), low distortion (<0.01% THD) sinewave oscillator drives the experiment with an output level which is programmable from 0.1mV to 2.55V rms for simplified $\Delta T_c/\Delta I_s$ or $\Delta T_c/\Delta H$ profiling. Fifth, measurement at much, much lower current levels (e.g. 10 µA) can be accomplished. On top of this, a single instrument does the job, and its operation can be automated under GPIB or RS–232 control.

Note the use of the relatively low ac excitation frequency of 10 Hz to prevent inductive and capacitative coupling from drive to input. Also observe the use of a shielded, twisted

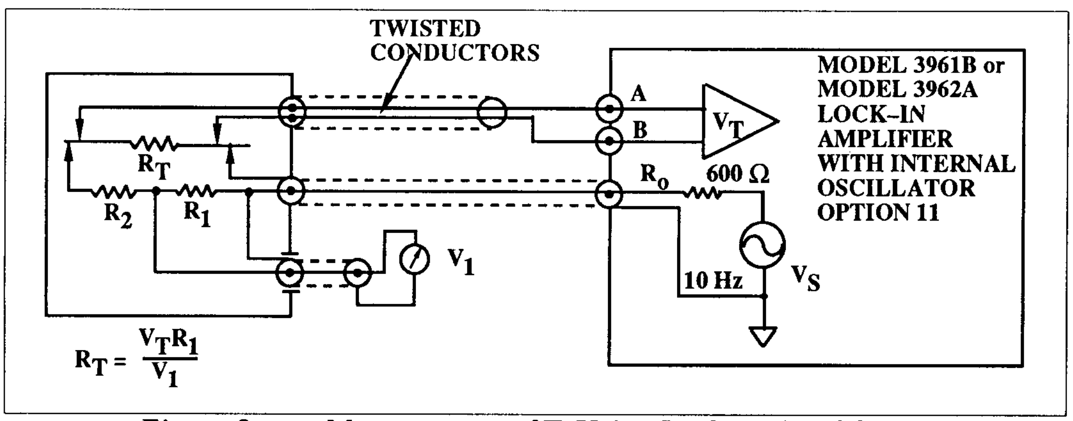

Figure 2 ac Measurement of T_c Using Lock–In Amplifier pair hooking up to the true differential input of the lock–in. The auxiliary voltmeter V1 obtains a current reading independent of drive–to–sample contact resistance and as well affords a means for monitoring this resistance. It can be implemented by conventional lab instrumentation, however a lock–in amplifier will yield better rejection of interferring noise. The measurement can be accomplished either by a low–cost secondary lock–in such as ITHACO Model 3921 (which can have its output digitized via the EXT DC input of a 3961B/3962A instrument), or by momentarily switching over the primary lock–in.

Example #1
Lock–In Without Preamplifier
(see Figure 2)

I_s = Drive Current = 4.00 mA (R_1 = 37.5Ω, R_2 = 0, V_s = 2.55V)

T = Lock–In Time Constant = 0.3 sec @ 12 dB/octave
(99% risetime = 6.6T = 1.98 seconds)

B = Measurement Equiv. Noise BW = 1/(8T) = 0.417 Hz

e_n = Lock–In Self Noise @ 10 Hz = $10\text{nV}/\sqrt{\text{Hz}}$

R_n = Resistance Noise (± uncertainty) = $e_n\sqrt{B}/I_s$ = 1.61, μΩ rms

Here we're approximated as closely as possible the conditions prevailing for the dc measurement alluded to above. To make a fair comparison of rms fluctuations with worst case dc error, we ought to convert rms values to crest values by multiplying by three (3 σ deviation). Thus for the same two second measurement time and with less than half the current, we've achieved a better than a five fold improvement in signal reproducibility (4.85μΩ peak vs 25μΩ). At identical 10 mA current levels (using an external current source), this would be a 13 fold advantage for the lock–in method. By switching in a large value external load resistor this setup can also measure high resistance levels, (e.g. R_T = 100KΩ for R_S = 100KΩ). This example assumes that the IR drop due to drive–to–sample contact resistance has negligible effect on drive current. It also assumes that the sample to lock–in contact resistances are small enough not to generate appreciable Johnson noise compared to the instrumentation noise e_n. To meet the latter condition, the sum of the two instrumentation contacts should not exceed approximately $R < (e_j)^2/(4KT)$.[1] If we take $e_j = 5\text{nV}/\sqrt{\text{Hz}}$ and T = 77°K, then the V_T contacts should total 6KΩ or less, for example.

Figure 3 shows a variation on the Figure 2 setup using a remote differential preamplifier. The ITHACO Model 1681 is somewhat noisier than using the lock–in alone (20 nV/√Hz vs 10 nV/√Hz @ 10 Hz), but potentially has two important advantages over direct connection to the lock–in. First, by remotely installing the preamp, one minimizes pickup of interference by keeping interconnecting wiring lengths to the experiment short. Second, and despite published specifications to the contrary, the actual in–system common mode rejection performance will probably be much superior. Figure 3 also depicts transformer coupling of the drive current, which might be required in any of the Figures 2, 3, or 4, in order to solve grounding and isolation problems. Note the use of the 3960V1 cable set to supply preamp dc power from the lock–in. The cable set includes the 3960V2 single ended to differential signal cable which has a built in bypass capacitor as shown.

[1] $K = 1.38 \times 10^{-23}\ V^2/(\Omega°K)$

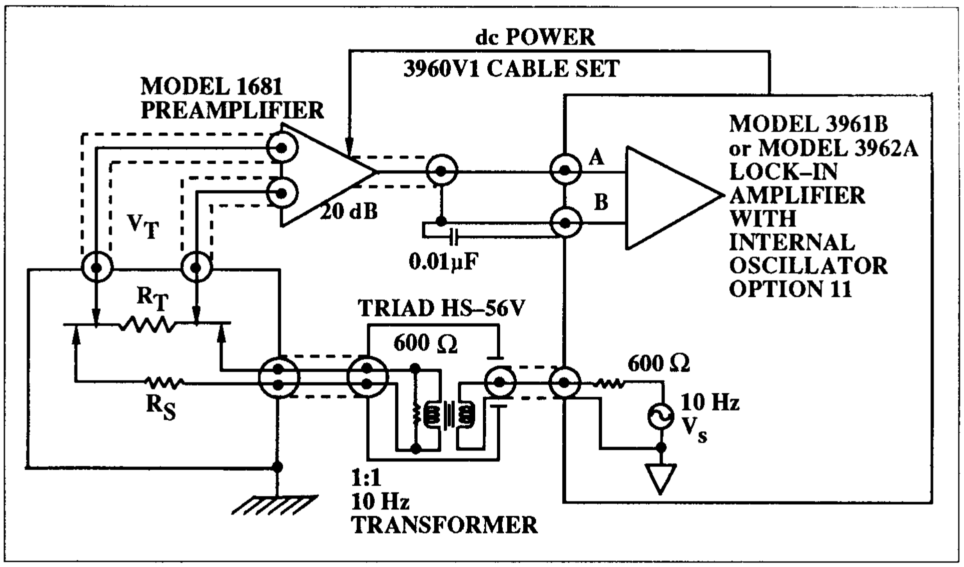

Figure 3 Use of Remote Differential Preamplifier

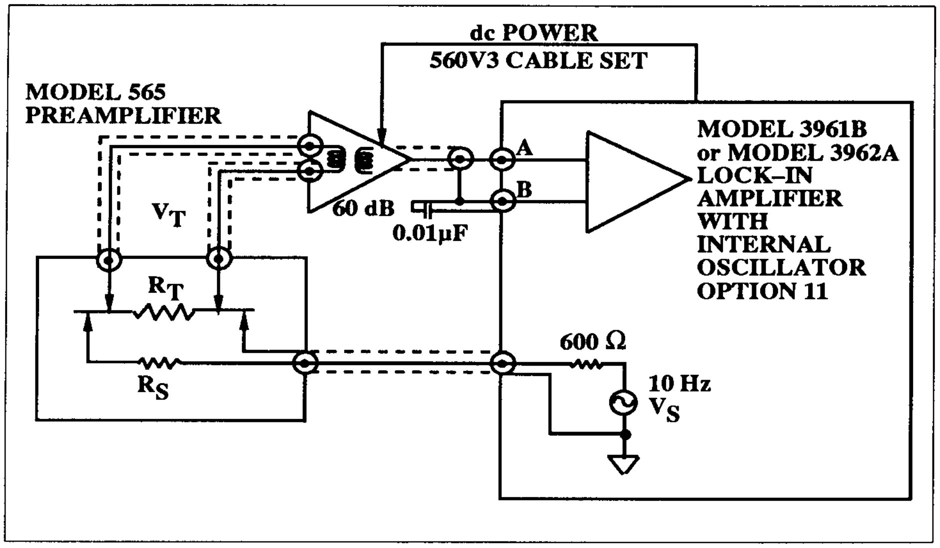

Figure 4 Improved Performance Using Ultra Low Noise, Transformer Coupled Preamplifier

Example #2
Use of Model 565 Preamplifier to Increase Resolution/Speed
(see Figure 4)

I_s = 1 mA (R_s = 1.95K, V_s = 2.55V)

T = 0.3 sec (99% t_r = 2 sec)

B = 1/(8T) = 0.417 Hz

e_n = 0.2 nV/$\sqrt{Hz}$ at 10 Hz (preamp noise)

R_n = en$\sqrt{B}$/Is = 0.129µΩ rms

If we had used I_s = 4.00 mA, as in Example #1, then the noise would be only 0.032µΩ (50 times more accurate than lock–in without preamp). For a 10 mA drive (comparison to dc conditions), the uncertainty becomes a mere 0.0129 µΩ rms (25µΩ ÷ (3 x 0.0129 µΩ) = 650 times more accurate).

Note the differential connection to the 565 preamp, which being remotely mounted near the experiment, reduces greatly the potential for extraneous pickup. The 560V3 Cable set includes the 3960V2 single ended to differential signal input cable shown in Figure 4. The disadvantage of this preamp is a lower allowable resistance range, giving good accuracy only for source resistances (R_T plus sample–to–preamp contact resistance) below a few tens of ohms at 10 Hz, as shown in Figure 5.

The very low noise characteristics of the Model 565 allows a lot of freedom in trading off current, speed and reproducibility. For example one could reduce the lock–in time constant to 30 milliseconds (about the limit, due to synchronous ripple in the lock–in output) allowing a 10 fold speed increase to 200msec/sample at the expense of an ~ 3 fold increase in error (from .129 µΩ rms to $\sqrt{10}$ larger, or .408 µΩ rms). Note that this improvement in system noise can only occur for low sample–to–preamp contact resistances resulting in less junction noise e_j than the e_n = 0.2nV/$\sqrt{Hz}$ Johnson noise of the 565 preamp. Assuming we want $e_j \leq .1$ nV/$\sqrt{Hz}$ at 77°K, R $\leq (e_j)^2/(4KT)$ = 2.3Ω, which is consistent also with the frequency response considerations depicted in Figure 5.

Alternatively one might wish to operate with 10 µA drive current. For T = 0.3 sec

$$R_n = e_n\sqrt{B}/I_s = e_n\sqrt{1/(8T)}/I_s$$

$$= 0.2\ \text{nV}/\sqrt{8 \times .3}\ /\ 10^{-5} = 12.9\ \mu\Omega\ \text{rms}$$

If this reproducibility were unsatisfactory, then one could have the lock–in perform signal averaging to trade speed for accuracy, as explained in the Model 3961B or Model 3962A Operator's Manual Prefaces. For example, if N = 256 @ t_s = 0.1 sec, then t_m = 25.6 sec and B = 1/(2t_m). Therefore:

$$R_n = 0.2\ \text{nV}/\sqrt{2t_m}/10^{-5} = 2.80\ \mu\Omega\ \text{rms}$$

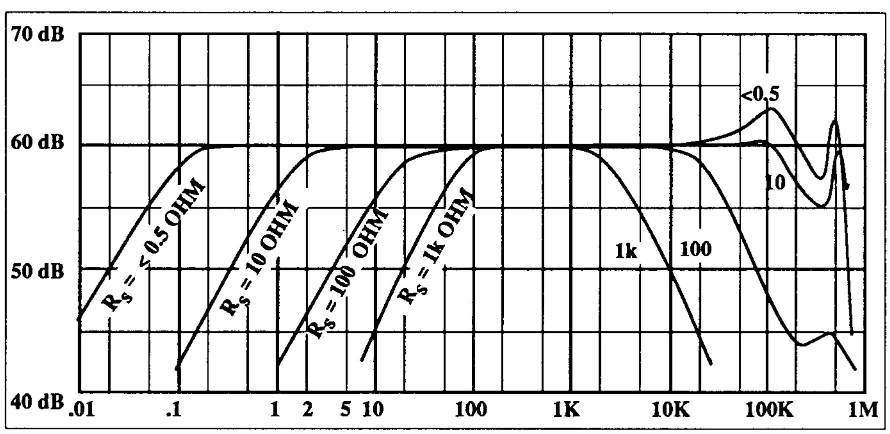

Figure 5 Typical Frequency Response For Model 565 in Transformer Mode

References:

1. Keithley Lab Note
   "Automating Resistanc Measurement on High Temperature Superconductors"

2. ITHACO Instruction and Maintenance Manual for Model 3961B Lock–In Amplifier

3. ITHACO Instruction and Maintenance Manual for Model 3962A Lock–In Amplifier

4. ITHACO IAN 49
   "Speed/Accuracy Tradeoff When Using A Lock–In Amplifier to Measure Signal in the Presence of Random Noise"

5. Rose–Innes and Rhoderick, *"Introduction to Superconductivity"* Second Edition, 1978. Pergamon Press Ltd. ISBN 0–08–021651–X