

MICROWAVE NOISE PARAMETER MEASUREMENTS OF A HIGH TEMPERATURE SUPERCONDUCTING FLUX FLOW TRANSISTOR\*

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**Abstract**

The noise parameters of a HTS flux flow transistor made of TlBaCaCuO operating at 77 K and 3-5 GHz have been experimentally determined. It is assumed that the dominant noise mechanism of the device, which is based on an array of weak links with a magnetic control line is due to the statistical nature of flux nucleation and motion in the links. The noise parameters dictate the dependence of the noise figure on the source impedance and were calculated by measuring the noise figure with a number of different source impedances. Sensitivity analysis is used to estimate the accuracy of the measurements. The measurements indicate a minimum noise figure of less than 1 dB at 3 GHz.

**Introduction**

We have been investigating a single layer superconducting device made on high Tc or low Tc materials. Such a device has shown gain at high frequencies<sup>1</sup> and several potential applications have been studied<sup>2,3,4</sup>. Here we report on the noise performance of one of these devices made on TlBaCaCuO and operating at 77 K.

The device (Fig. 1) is based on a parallel array of weak links biased into a flux flow regime. In this state fluxons are admitted to the links and travel in the direction perpendicular to the bridge length. Nucleation of the fluxons is controlled by an external line that generates magnetic field. This provides a transresistance effect from the control line port to the port that is biasing the links.

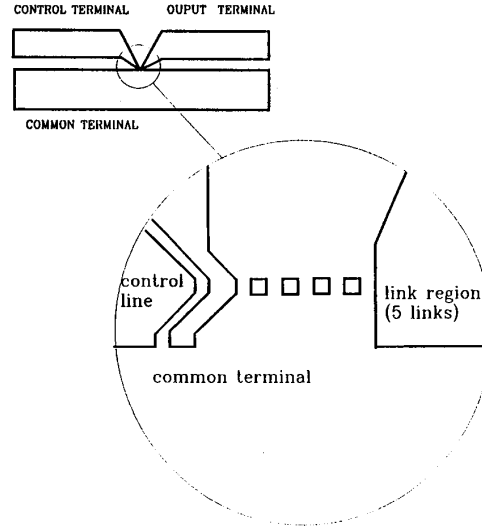
The device tested was made of TlBaCaCuO on a LaAlO<sub>3</sub> substrate. Patterning was done with conventional lithography and a timed etch of dilute HNO<sub>3</sub> solution. The links are approximately 10µm in length and 5µm in width. After the links are formed, the entire link region is thinned in another acid etch to favor fluxon nucleation.

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Fig. 1: Physical layout of the device



**Basic Equations**

Noise characterization of devices is usually done in terms of noise figures or noise temperatures. The noise figure of a two-port is defined as<sup>5</sup>:

$$F = \frac{N_o}{G_a N_i} \quad (1)$$

where N<sub>i</sub> and N<sub>o</sub> are the noise power at input and output respectively, and G<sub>a</sub> is the available gain of the device (power available at the output/ power available at the input). This can be related to the noise temperature through<sup>5</sup>:

$$F - 1 = \frac{T_e}{T_o} \quad ; \quad T_o = 290^\circ K \quad (2)$$

When several two-ports are cascaded, their overall noise figure is given by<sup>5,6</sup>:

$$F = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \dots \quad (3)$$

where  $F_i, G_i$  are the noise figure and available gain of the  $i$ -th device (numeration starting from the input side).

The noise figure of a two-port depends on the admittance of the source to which it is connected through the equation<sup>6</sup>:

$$F = F_{min} + \frac{R_n}{G_s} |Y_s - Y_o|^2 \quad (4)$$

where  $Y_s = G_s + jB_s$  is the source admittance and  $F_{min}, R_n$  and  $Y_o$  are referred as the noise parameters of the device, since they determine the functional dependence of  $F$  with  $Y_s$ .

In this work the noise parameters of an Abrikosov vortex flow transistor (AVFT) have been experimentally determined by measuring its noise figure under a number of different source admittances and fitting Eq. 4. These noise parameters include the effects of access cabling, bias tees and launchers, which makes the minimum noise figure determined an upper bound of that of the transistor itself.

Noise Figure Measurement System

Most of the instrumentation used for noise figure measurement is appropriate only if the device under test (DUT) is matched to the source<sup>7</sup>. Recently, measurement schemes have been developed to overcome that problem and are mainly applied to microwave and millimeter wave FETs<sup>8,9</sup>. Flux flow transistors are extremely mismatched devices (their input and output impedances are much lower than the 50  $\Omega$  reference commonly used in high frequency systems), which makes the use of these new schemes indispensable.

The measurement scheme used<sup>9</sup> is shown in Fig. 2. With this setup, the noise source is first connected to the receiver (RCV) and its noise figure is read with the HP8970 meter. The DUT is then inserted and the overall noise figure of the DUT and RCV is read. Since the noise figure of the detection system (DS in Fig. 2) remains constant in both cases due to the effect of the output isolator (OI), the noise figure of the DUT can be found using Eq. 3 and the fact that in passive networks, the noise figure is the inverse of the available gain<sup>5</sup>:

$$F_{dut} = F_{rd-ns} - \frac{F_{rcv-ns} \left( \frac{G_{av-oi-ns}}{G_{av-oi-dut}} \right) - 1}{G_{av-dut}} \quad (5)$$

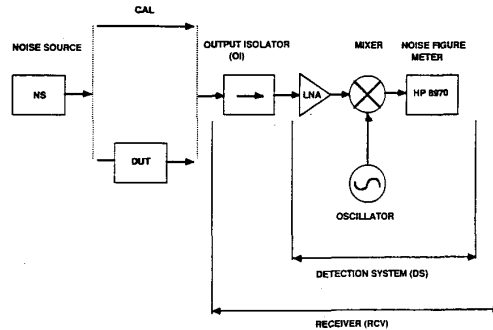
where:

- F<sub>dut</sub>= noise figure of the DUT
- F<sub>rd-ns</sub>= uncorrected noise figure of DUT+RCV
- F<sub>rcv-ns</sub>=uncorrected noise figure of the RCV when connected to the noise source (no DUT inserted)

- G<sub>av-oi-ns</sub>=Available gain of the output isolator when connected to the noise source
- G<sub>av-oi-dut</sub>=Available gain of the output isolator when connected to the DUT.
- G<sub>av-dut</sub>=Available gain of the DUT when connected to the noise source.

Knowledge of the S-parameters of the OI and DUT is necessary to calculate the above available gains.

FIGURE 2: NOISE FIGURE MEASUREMENT SYSTEM

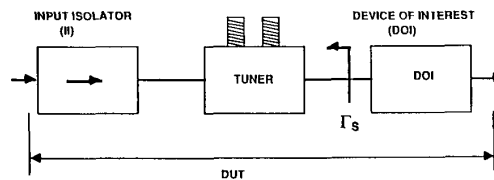


Noise Parameter Determination

The noise figures obtained with the setup of Fig. 2 are measured with the DUT connected to a 50 ohms source (the noise source). To determine noise parameters it is necessary to measure noise figures under a number of different source impedances. The setup of Fig. 2 has been used for this purpose by using as a DUT the elements shown in Fig. 3. The noise figure of the device of interest (DOI) can be found after the noise figure of the DUT is determined as indicated before and the noise contributions of the input isolator (II) and tuner are removed using Eq. 3. The S parameters of II, tuner and DOI are needed to calculate the available gain and noise figure of the DUT (see Eq. 5), remove the effects of passive networks (tuner and II) and determine the source reflection coefficient of the DOI ( $\Gamma_s$ ).

Since there are four real noise parameters to be found ( $F_{min}, R_n$  and  $Y_o = G_o + jB_o$ ), the noise figure of the DOI ( $F_{doi}$ ) must be determined for

FIGURE 3. DUT FOR NOISE PARAMETER EXTRACTION



at least four different  $\Gamma$ s. Previous works<sup>8,10,11</sup> show that when only 4 sets of source admittances (or equivalently,  $\Gamma$ s) are used, the resulting noise parameters are highly sensitive to errors in  $\Gamma$ s. Least square fitting algorithms are used to match the measured noise figures and source admittances while determining the noise parameters through Eq. 4. The specific source admittances to be presented to the DOI are selected to minimize the error sensitivity mentioned above<sup>10</sup>, and their associated reflection coefficients form a cross-shape on the Smith chart. In this work, we intended to use the following set of  $\Gamma$ s :

$$0.7 < 180^\circ ; 0.7 < 0^\circ ; 0.6 < 90^\circ ; 0.6 < -90^\circ ; \\ 0.3 < 90^\circ ; 0.3 < -90^\circ$$

(6)

### System Verification

The proper operation of the measurement system and the software developed to determine Fdoi has been checked by including passive circuits as DOI (see Figs. 2,3). The noise figure of any passive two-port at room temperature (290 °K) is given by the inverse of its available gain<sup>5</sup>, thus the accuracy in Fdoi can be assessed by comparing the inverse of the available gain of the DOI (which is found<sup>6</sup> from its S parameters and  $\Gamma$ s) and Fdoi calculated as outlined above. This error has been calculated for the set of  $\Gamma$ s of Eq. 6 and it has been noticed that it tends to increase as  $|S_{11}|$  and  $|S_{22}|$  grow (i.e. for mismatched devices). For the mismatch levels of our DOI, typical errors were less than 10 %

### Experimental procedure and results

1) The noise figure of the receiver (RCV) when connected to the noise source (NS) was measured (see Fig.2 and Frcv\_ns in Eq. 5).

2) The S-parameters were measured for the input isolator (II), device (DOI) and output isolator (OI). These will remain constant throughout the experiment.

3) The slide-screw tuner (Fig. 3) was adjusted to present to the device (DOI) the reflection coefficients of Eq. 6. After each adjustment, the S-parameters of the tuner were measured (so that the actual source reflection coefficients would be used instead of those of Eq. 6) and the noise figure of the cascaded DUT+RCV (see Fig.2 and Frd\_ns in Eq. 5) was measured with the HP8970 meter.

4) The results were processed with a FORTRAN program that we developed. For each data set corresponding to the different positions of the tuner, the program determines  $\Gamma$ s accurately, calculates Fdut through Eq. 5, Fdoi with Eq. 3 and performs a least square fit of the results

to Eq. 4, from which the noise parameters are extracted. An error table is then generated to compare the noise figures measured with those calculated from the noise parameters and Eq. 4. This helps to discern measurement points that deviate largely from the average trend due to experimental errors. In our case (see Table 1) point number 3 had a much larger deviation from the general trend than the rest, and was ignored in a subsequent noise parameter calculation (Table 2). The disregarding of this data point raised the concern that high error sensitivity may occur, since the configuration of  $\Gamma$ s of Eq. 6 was no longer used. However, numerical criteria developed in a previous work<sup>10</sup> and a perturbation analysis (see Table 3) showed that the problem was numerically well-behaved.

**Table I:** Least square fitting of noise parameters

Point	$\Gamma$ s	Fdoi(meas) dB	Err %
1	0.66<172.6°	4.51	-2.4
2	0.75<-1.7°	4.12	7.8
3	0.56<91.5°	5.47	-54.8
4	0.68<-88.8°	2.20	0.9
5	0.27<75.5°	1.61	5.9
6	0.33<-85.1°	1.51	8.3

Resulting noise parameters:

$$F_{min}=1.32 \text{ dB}; \Gamma_0=0.45<-74^\circ ; R_n=20.4\Omega$$

**Table II:** Data from table I, excluding point 3.

Point	1	2	4	5	6
Err(%)	-9.4	0.3	-12.8	-10.2	-8.1

Resulting noise parameters:

$$F_{min}=1.26 \text{ dB}; \Gamma_0=0.21<-59^\circ ; R_n=21.0\Omega$$

5) Step 3 was repeated, but instead of using the source reflection coefficients of Eq. 6 the tuner was adjusted to present to the device the optimum  $\Gamma$ s shown in Table 2 and the noise figure of the device (Fdoi) was determined as before. This process was repeated by readjusting the tuner to several  $\Gamma$ s close to  $\Gamma_0$  and determining Fdoi for each  $\Gamma$ s so that a gradient search of the optimum source reflection coefficient was made. The results are shown in Table 4. Point number 12 resulted in the lowest Fdoi found (0.93 dB for  $\Gamma_s=\Gamma_0=0.17<-83^\circ$ ).

**Table III:** Error sensitivity analysis for data of Table II

Max. orthogonality factor (see ref. 10):

$$|\cos(V_i, V_j)| < 0.76$$

Max. variation to a perturbation in  $\Gamma_s$  of magnitude 0.01:

$$F_{min}: 0.63\% ; R_n=4.6\% ; \Gamma_o: 0.012$$

**Table IV:** Fdoi vs.  $\Gamma_s$ 

Point	$\Gamma_s$	Fdoi (dB)
7	0.17<-98°	1.20
8	0.13<-98°	1.13
9	0.21<-74°	2.31
10	0.15<-49°	1.07
11	0.11<-59°	1.32
12	0.17<-83°	0.93
13	0.22<-82°	1.14
14	0.22<-78°	1.55

### Conclusions

A two-step measurement system has proved effective in determining noise parameters of superconducting devices. Consistency in the results is assured by two facts:

a) The measured noise figure of passive devices agreed with its theoretical value, calculated from S parameter measurements.

b) The noise parameters of the active device were determined with two independent experiments. In the first one, the noise figure of the device was measured for a set of source reflection coefficients that spans the Smith Chart, and the corresponding noise parameters were calculated. In the second experiment, reflection coefficients in the vicinity of the optimum reflection coefficient were used. The results confirm the validity of the first experiment and provide a more accurate estimate for  $F_{min}$  and  $\Gamma_o$  (optimum source reflection coefficient).

The noise parameters of a AVFT (including the effects of access cables and launchers) have been determined as outlined above. The values of  $F_{min}$  and  $\Gamma_o$  are accurately determined by the second experiment. As for the remaining noise parameter ( $R_n$ ), along with  $G_s$  (Eq. 4) dictates how fast the noise figure deteriorates when  $\Gamma_s$  deviates from  $\Gamma_o$ . Accurate estimation of its value requires the source reflection coefficients to be spread over the Smith chart<sup>8</sup>, so the value resulting from the first experiment is expected to be the most accurate. Accordingly, the final values of the noise parameters are (from Tables 1 and 2) :

$$F_{min}=0.93 \text{ dB} \quad \Gamma_o=0.17<-83^\circ \quad R_n=21 \Omega$$

The low  $F_{min}$  measured on this single device contradicts our initial expectations, since the nucleation of fluxons or flux bundles should be quite noisy. Consequently, we intend to repeat the measurements on new devices as they become available.

### Acknowledgement

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### References

1. J.S. Martens, G.K.G. Hohenwarter, J.B. Beyer, J.E. Nordman and D.S. Ginley. "S parameter measurements on single superconducting thin film three terminal devices made of high Tc and low Tc materials". Journal of Applied Physics. May 1989.
2. J.S. Martens, J.B. Beyer, J.E. Nordman and D.S. Ginley. "A broadband microwave linear phase modulator made of high Tc superconductors". Microwave and Optical Technology letters. February 1990.
3. J.S. Martens, J.B. Beyer, J.E. Nordman, G.K.G. Hohenwarter and G.S. Ginley. "A superconducting single film device oscillator made of high Tc and low Tc materials". 1989 IEEE MTT-S symposium digest.
4. J.S. Martens, J.B. Beyer, J.E. Nordman, G.K.G. Hohenwarter and G.S. Ginley. "A Josephson Junction to FET High Speed Line Driver Made of TlCaBaCuO". Presented to the 1990 Applied Superconductivity Conference.
5. F.G. Stremler. "Introduction to Communication Systems", second edition. Addison-Wesley 1982.
6. Guillermo Gonzalez. "Microwave Transistor Amplifiers. Analysis and Design". Prentice-Hall 1984.
7. Hewlett Packard. Product Note 8970 A-1. "Applications and Operation of the 8970A Noise Figure Meter". October 1982.
8. Davison, A.C.; Leake, B.W.; Strid E. "Accuracy Improvements in Microwave Noise Parameter Measurements". IEEE Trans. MTT Vol MTT-37 No. 12 December 1989.
9. Jyoti Mondal. Private communication. To be presented to IEEE Trans. MTT.
10. J. O'Callaghan, J. Mondal. "A Vector Approach for Noise Parameter Fitting and Selection of Source Admittances". Manuscript presented to IEEE Trans. MTT.
11. R.Q. Lane. "The Determination of Noise Parameters". Proc. IEEE 1969, 57 pp. 1461-1462.