Conf-9106224--1

SAND--91-1272C

DE91 014702

The Superconducting Flux Flow Transistor: Models and Applications

J. S. Martens, V. M. Hietala, T. E. Zipperian, D. S. Ginley and C. P. Tigges

Sandia National Laboratories, Department 1140, Albuquerque, NM 87185, USA

Abstract

The superconducting flux flow transistor (SFFT) is a single film, active device generally made from high temperature superconducting (HTS) materials. The device is based on the magnetic control of flux motion, has gain and can operate to over 40 GHz with 3 μm feature size. Existing models are reviewed along with the latest equivalent circuit values derived from S-parameter measurements. Noise performance is compared to that predicted by a relatively simple flux noise model and recent amplifier performance is discussed.

1. Introduction

The SFFT is being investigated (e.g., [1]-[3]) as an HTS device for high speed applications. Toward that goal, extensive simulations and microwave characterizations have been performed to refine the device and determine the device's ultimate performance limits. A more immediate result is the ability to better predict behavior in current applications.

2. Device Basics

The basic structure of the devices tested is shown in Fig. 1 and consists of an SFFT cell embedded in coplanar waveguide for microwave measurements. The body of the device consists of a parallel array of weak links through which the main bias current (I_{bdy}) passes. Each link is typically 10 μm by 3 μm and is 50-100 nm thick (etched from a film thickness of 300-400 nm). A separate control line provides a local magnetic field that modulates the flux density in the link system.

When the body of the device is biased below the critical current (on the order of 1 mA) no flux is admitted into the link system. Above the critical current both vortex/anti-vortex pairs (self-field) and single vortices (from external field) are admitted. The vortices are subject to 'Lorentz' forces from bias and external fields, viscous damping, pinning forces (which are undesirable in that the average vortex speed is reduced) and surface barriers at the edges of the links which hamper flux

entry and exit. The balance of these forces determines the flux motion and hence the terminal voltage.

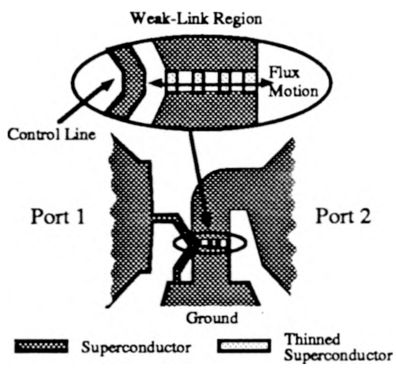

Figure 1. A layout of the superconducting flux flow transistor. Port 1 is the control line and port 2 is the device body. The transmission line ground planes are above and below the section shown.

The device behavior is closely correlated to the quality of the film remaining in the link region. High pinning reduces sensitivity to external magnetic fields (and hence gain) and reduces the flux speed and frequency response of the SFFT. A low H_{c1} allows easier flux entry into the system, increasing sensitivity to the control fields. The penetration depth strongly influences the surface barriers and hence control-field sensitivity [4]. Maximum gain occurs for links thinner than a penetration depth but not so thin that the superconductivity is destroyed or the defect density rises enough to induce excessive pinning centers.

Sample IV curves for a $Tl_2Ca_2Ba_2Cu_3O_{10}$-based device at 77K are shown in Fig. 2. The zero-voltage and flux flow states are clearly illustrated. At high bias currents, the links are driven completely normal. Upon application of a control current, a given bias point suffers a nearly horizontal translation as is consistent with a flux density change. A transresistance element is therefore the logical choice for the active element in the equivalent circuit.

3. An Equivalent Circuit

The primary equivalent circuit used is shown in Fig. 3. The input or control line side is a superconducting short with some inherent inductance and resistance (the latter arising from microwave surface resistance and some contact resistance). The transresistance element discussed above is shown on the output side. There is a finite output resistance arising from the presence of the normal vortex cores. The output inductance has significant kinetic contributions because of the extreme thinness of the links. The output resistance, output inductance and transresistance are bias dependent. The non-linearity of the link (or output) inductance allows the development of efficient, low-loss phase shifters [2]. The values of the parameters are derived through mechanistic simulation (of flux motion), moment method calculations [3], DC measurements and through fitting microwave S-parameter data [2].

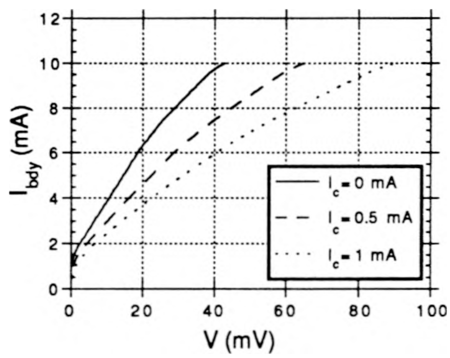

Figure 2. IV curves of a TlCaBaCuO SFFT. I_{bdy} is the current through the device body (link region) and I_c is the control current. The voltage V is measured across the link system.

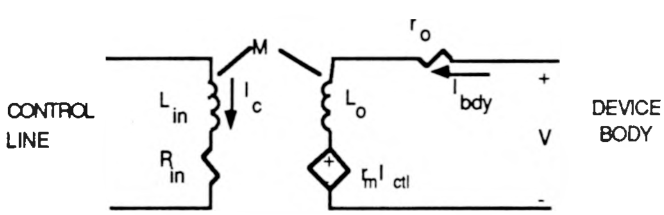

Figure 3. An equivalent circuit of the SFFT. The transresistance element is the active element. Other interesting features include the non-linearity of the output inductor and the low amount of cross-talk (M is typically 10 pH). Other typical component values are r_m=21 Ω (transresistance), r_0=4 Ω (output resistance), L_{in}=100 pH, L_{out} = 70 pH, R_{in}= 0.05-0.1 Ω (at moderate bias).

4. Noise Mechanisms and Performance

We will concentrate on broadband flux noise and its effects on microwave performance. Based on simulations and some flux speed measurements [3], the vortices tend to move through the link system in bundles of variable size. The noise can then be thought of as a doubly stochastic Poisson process with the two random variables: the size of a bundle and the time of its occurrence. The key parts of this argument have been previously derived by Huebner [5]. In the frequency range far from DC (so that $1/f^{\alpha}$ effects are small) but well below the frequencies where transit time effects are important ($\approx$ 30 GHz with the present devices), the spectral density of this flux noise can be approximated as [6]

$$G_{midband} \approx \left(\frac{\hbar\pi}{2e}\right)^2 \left[2B + \frac{B^2}{K}\right] \quad V^2 \text{ in a 1 Hz BW} \quad , \tag{1}$$

where B = number of vortices moving past an observation point per unit time within a bundle (an average density of vortices within a bundle) and K = number of bundles moving past an observer per unit time. Estimates for these two parameters have been obtained using the mechanistic simulations discussed above and flux speed experiments [3]. For a typical Tl device at moderate bias levels (about half way between the zero voltage branch and the normal switch-over), B$\approx$ 1-2 x 10^{11} 1/s while K $\approx$ 0.5-1 x 10^{11} 1/s. It should be noted that both of these parameters will be bias dependent (both increase with bias). These estimates should be valid from a few MHz to at least 10 GHz based on the relevant time constants and estimates of the extent of the 1/f noise from other work (e.g., [7]).

The noise factor of an unmatched SFFT amplifier at low microwave frequencies (up to a few GHz perhaps) would then be

$$F \approx 1 + \frac{R_{source}}{4kTr_m^2}\left\{\left(\frac{\hbar\pi}{2e}\right)^2\left[2B + \frac{B^2}{K}\right] + 4kT'r_0\right\} , \tag{2}$$

where R_{source} is the source resistance, T=300K (source resistance temperature) and T'=77K (SFFT output resistance temperature). For the parameter estimates listed above , the noise figure $\approx$ 4.8 - 7 dB. This ignores the filtering effects of the parasitics in the circuit.

To test this hypothesis, the noise of several SFFTs was measured as a function of bias. The bias range was kept small to avoid large shifts in the model parameters (small changes were accounted for in the calculations). The device was probed with spring-loaded coplanar probes and the noise measured using a Cascade Microtech Noise Measurement system. Plots of the measured noise figure of a

TlCaBaCuO SFFT (2 GHz, 77K) and that predicted from simulations are shown in Fig. 4. The simulations used the equivalent circuit of Fig. 3 (with de-embedded parameter values), the noise voltage of Eq. 1 and experimentally determined launch parasitics. At least over this bias range, the model fits well. Shot-like flux noise is probably the dominant contributor to device noise at these frequencies.

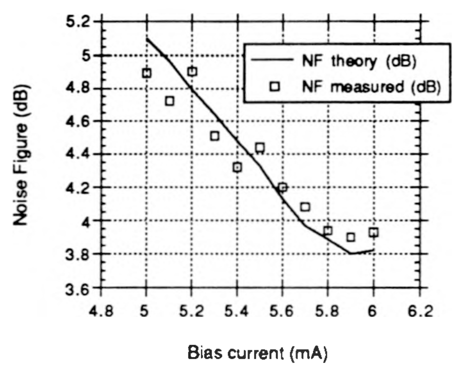

Figure 4. Theoretical and measured noise figure of an unmatched SFFT as a function of bias (2 GHz).

5. Applications and Model Predictions

One obvious application is a matched amplifier (a single SFFT with input and output passive impedance-matching networks). The gain of such a circuit along with that predicted by the model is shown in Fig. 5. Maximum available gain, computed from device S-parameter measurements, is on the order of 20 dB, so improvement is possible. The noise figure for this amplifier in a 50 Ω system was about 3.1 dB (estimated from minimum noise figure measurements using the Cascade system) while that predicted by the model was 3.45 dB.

6. Conclusions

We have presented some recent results of work on the SFFT. The latest designs have tried to minimize excess inductances while increasing transresistance. The results has been verified by S-parameter measurements which show input inductances ≈ 100 pH and transresistance > 20 Ω. Noise calculations and measurements have been performed suggesting that shot-like flux noise is dominant for linear microwave applications and that typical noise figures are in the several dB range. Matched amplifiers are being made with gains > 10 dB over a bandwidth > 1 GHz.

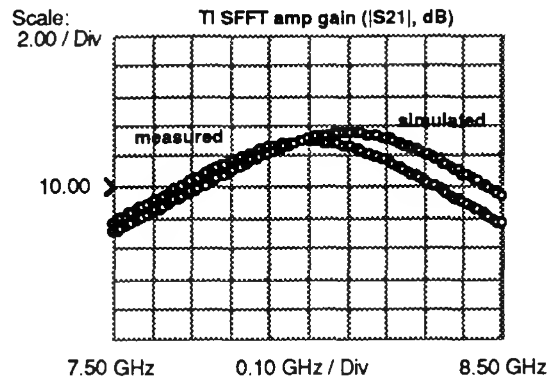

Figure 5. Performance of a matched Tl SFFT amplifier (77K).

7. Acknowledgments

This work was supported by the U.S. Department of Energy under contract No. DE-AC04-76P00789.

8. References

[1] J. S. Martens, J. B. Beyer, J. E. Nordman, G. K. G. Hohenwarter and D. S. Ginley, IEEE Trans. on Mag, vol. MAG-27, 3284 (1991).

[2] J. S. Martens, V. M. Hietala, T. E. Zipperian, D. S. Ginley, C. P. Tigges, and J. M. Phillips, "S-parameter Measurements and Applications of Superconducting Flux Flow Transistors," presented at the 1991 IEEE MTT-S International Microwave Symposium, Boston, MA USA, 11-13 June 1991.

[3] J. S. Martens, D. S. Ginley, J. B. Beyer, J. E. Nordman and G. K. G. Hohenwarter, IEEE Trans. Appl. Super., vol. 1, (June 1991).

[4] T. Van Duzer and C. W. Turner, Principles of Superconductive Devices and Circuits (Elsevier, New York, 1981), chp. 3.

[5] R. P. Huebner, Magnetic Flux Structures in Superconductors, (Springer-Verlag, Berlin, 1979).

[6] J. W. Goodman, Statistical Optics, (Wiley, New York, 1985), chps. 2-3.

[7] F. C. Wellstood, J. J. Kingston, M. J. Ferrari and J. Clarke, IEEE Trans. on Mag., vol. 27, 2569 (1991).