Superconducting Bolometric Mixers

H. Ekström, B. Karasik, E. Kollberg, *Fellow, IEEE,* and S. K. Yngvesson, *Senior Member, IEEE*

Abstract—**Mixing at 20 GHz in niobium superconducting thin-film strips in the resistive state is studied. Experiments give evidence that electron-heating is the main cause of the nonlinear phenomena. The requirements on the mode of operation and on the film parameters for small conversion loss and the possibility of conversion gain are discussed. Measurements indicate a conversion loss between 1–8 dB and a DSB mixer noise temperature between 100 and 450 K at 20 GHz. The device output noise temperature at the mixer operating point can be as low as 30–40 K. A simple theory that is based on the assumption that the small signal resistance is linearly dependent on power is presented. This type of mixer is considered very promising for use in low-noise heterodyne receivers at THz frequencies.**

I. INTRODUCTION

RECENTLY PROPOSED hot-electron mixers utilizing thin superconducting films in the resistive state [1] have a potential to be competitive with traditional mixers in super heterodyne receivers at terahertz frequencies for radio astronomy and remote sensing applications. These new types of mixers have the advantage of simplicity over SIS and Schottky mixers both from the circuit and the technological point of view. This is particularly obvious in comparison with SIS trilayer mixers, which show excellent performance below 500 GHz. However, for frequencies above the gap frequency of the superconductors, the SIS mixers are not expected to perform as well. Schottky-diodes are known to work near and above 1 THz, but with lower sensitivity due to an increased noise temperature. The well-known InSb hot electron mixers are sensitive enough in the range 0.5–1 THz, but the IF bandwidth is too narrow for most practical applications. In this letter, we investigate the possibility of using the nonlinear effects in the resistive state of superconducting films for microwave mixing. Experiments at 20 GHz with small strips of nonlinear niobium elements indicate good mixer performance, i.e. low conversion loss and noise temperature. We judge that these results can be translated to the THz frequencies due to the nature of the electromagnetic interaction and nonlinearity of these devices. Indeed, mixing has been observed up to 1.5 THz for Nb [1]. This frequency is about two times the bandgap frequency.

Manuscript received May 13, 1994. This work was supported by the Swedish National Board of Industrial and Technical Development (NUTEK).

H. Ekström and E. Kollberg are with the Chalmers University of Technology, S-412 96 Göteborg, Sweden.

B. Karasik is with the Moscow State Pedagogical University, Moscow 119435, Russia.

S. K. Yngvesson is with the University of Massachusetts, Amherst, MA 01003 USA.

IEEE Log Number 9402971.

II. MIXER THEORY

A superconducting hot electron bolometer (HEB) consists of one or more thin superconducting strips, deposited on a substrate. The strips are heated by DC and microwave power to the neighbourhood of the superconducting-normal transition temperature, T_c. Some normal (hot) electrons are then produced in the strips and a nonzero resistance is measured. If the strips are sufficiently thin, the time constant for phonons in the superconductor to escape to the substrate, $\tau_{\mathrm{ph}-s}$, is shorter than the time constant for phonon electron collisions, $\tau_{\mathrm{ph}-e}$, and electron phonon collisions, $\tau_{e-\mathrm{ph}}$. Hence, it is possible to heat the electrons above the temperature of the lattice, contrary to the case of ordinary bolometers where the electrons and the lattice are heated to the same temperature. If LO and RF power is fed to the HEB device, a modulation of the electron temperature will create a voltage at the intermediate frequency (f_{IF}). The electron energy relaxation time must be short enough such that $\tau_{e-\mathrm{ph}} < (2\pi f_{\mathrm{IF}})^{-1}$. The energy relaxation time is material and technology dependent, resulting in an IF bandwidth of 50–300 MHz for Nb and several GHz for NbN [1], [2]. Also, the phonon escape time to the substrate is limited by the device geometry. Thus, the bolometer should be less than 100 Å thick and about 1 μm wide. The bolometer resistance may be adjusted by adding parallel strips and by changing the strip length. The absorption of microwave power by the normal electrons in the HEB is essentially frequency independent, and it will therefore operate to RF frequencies well into the THz range, i.e. much higher than the bandgap frequency of the superconductor. The purpose of the present effort is to carefully measure conversion loss and noise properties of the HEB at a low microwave frequency in order to establish a firm basis for the design of future THz HEB mixers.

The same simple expression for the conversion gain has previously been derived for two different HEB devices: for the superconducting HEB by employing an energy balance equation [1]; and for hot electron InSb mixers by the use of circuit theory [3]. A basic assumption is that the DC and RF *power* dependencies of the bolometer resistance are equal. One obtains

$$G = \frac{P_{\mathrm{IF}}}{P_s} = 2C^2 \frac{P_{\mathrm{LO}} P_{\mathrm{DC}}}{(R_L + R_B)^2} \frac{R_L}{R_B} \left(1 - C \frac{P_{\mathrm{DC}}}{R_B} \frac{R_L - R_B}{R_L + R_B}\right)^{-2} \quad (1)$$

where $C = dR_B/dP_{\mathrm{tot}} = dR_B/dP_{\mathrm{DC}}$. $P_{\mathrm{IF}}, P_s, P_{\mathrm{LO}}$ and P_{DC}, are the IF-, signal, LO- and DC-power, respectively. R_B and R_L are the bolometer and load resistances.

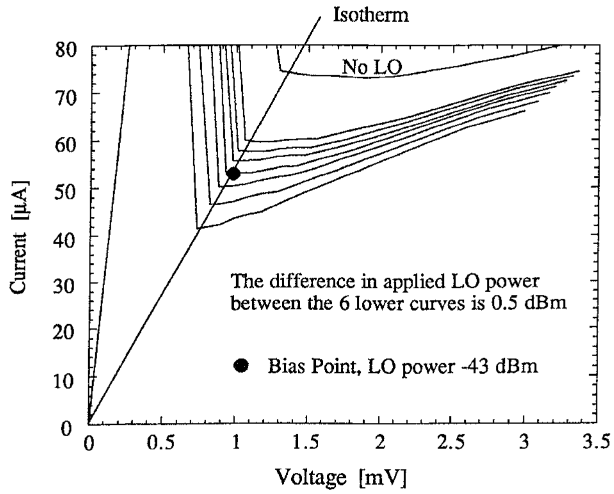

Fig. 1. IV curves for the bolometer (including $\approx 3\Omega$ series resistance) for different applied LO power. A typical bias point is also shown.

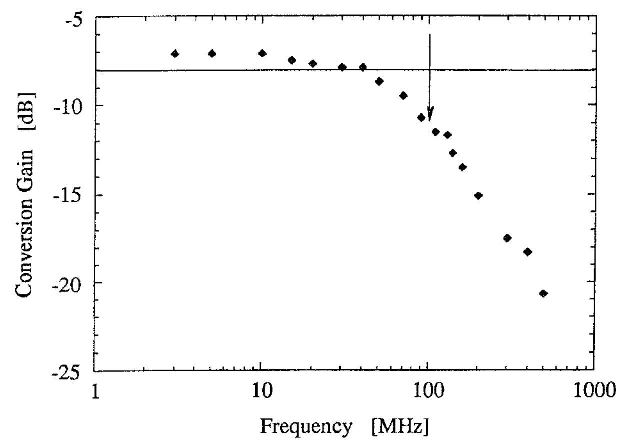

Fig. 2. Conversion gain as function of intermediate frequency, with a 3-dB cut-off at 100 MHz.

By tracing the DC IV-curve, one finds $\Delta R = (V + \Delta V)/(I + \Delta I) - V/I$ and $\Delta P = (V + \Delta V)(I + \Delta I) - VI$, which gives

$$C = \frac{R_B}{P_{\rm DC}} \frac{\left(\frac{dV}{dI}\right)_{\rm DC} - R_B}{\left(\frac{dV}{dI}\right)_{\rm DC} + R_B}$$

and

$$G = \frac{1}{2} \frac{P_{\rm LO}}{P_{\rm DC}} \frac{R_L}{R_B} \left(1 - \frac{R_B}{(dV/dI)_{\rm DC}}\right)^2 \left(1 + \frac{R_L}{(dV/dI)_{\rm DC}}\right)^{-2} \tag{2}$$

where $(dV/dI)_{\rm DC}$ is the derivative of the pumped IV in the bias point.

Equation (1) is valid for low intermediate frequencies, where the finite relaxation time of the device has no influence on the conversion gain. The fundamental limit of -6-dB gain derived in [3] is not necessarily valid for the superconducting HEB, where it could be possible to obtain negative differential resistance within the IF-band. As can be seen in (2), the gain will be infinite if $dV/dI = -R_L$.

III. Experiment

HEB's having two parallel niobium strips, 100–150 Å thick, 1.5 μm wide, and 7 μm long with normal resistance between 40 and 150 Ω have been manufactured on silicon substrate and measured at 20-GHz signal and 1–1000 MHz intermediate frequency. The bolometer/mixer is biased in the lower part of the resistive region (Fig. 1). The transition between the pure superconductive state and the resistive state at lower bias indicates a negative differential resistance necessary for positive conversion gain. However, this region is unstable and has so far not been used for mixing.

The lowest intrinsic conversion loss of seven investigated devices was around 1 dB at 20 MHz IF and 2.1 K, and the highest was around 8 dB. Generally, the best conversion is found for samples with the narrowest superconducting-normal transition ΔT_c, i.e. dR/dT is large [4]. The conversion is not very sensitive to temperature variations. The measured loss of the best mixer quoted above can be compared with 2-dB loss calculated from (1). The agreement is quite reasonable considering the very simple model, which only takes into account uniform heating of hot electrons. $P_{\rm LO}, R_B, P_{\rm DC}$, and dV/dI were obtained from the DC IV curve. The measured intrinsic conversion loss was obtained by deriving the RF coupling to the mixer from a set of IV curves recorded at different LO power. For details of this technique we refer to [4]. There is a 3-dB cut-off in the response of hot electrons at $\approx$100-MHz IF (see Fig. 2). There is also a response at lower IF around 1–10 MHz for slower processes, such as the relaxation of the normal domain size and back flow of phonons from the substrate. It is feasible to avoid the formation of normal domains, and thereby produce a more uniform absorption of RF power in the strips, by using one or more of several methods: 1) Application of a magnetic field, which reduces the superconducting energy-gap, 2) Use of higher frequencies comparable to the gap frequency of the superconductor, and 3) Increase of the lattice temperature to a value close to T_c.

The DSB receiver noise temperature of one of the HEB mixers was measured with a noise source to be between 470 and 690 K. The noise temperature of the IF amplifier was 120 K. A DSB mixer noise temperature between 100 and 450 K can be derived from these values, given the conversion loss of 7±1 dB. The large interval quoted is due to errors in determining the losses in components used for the measurement and the uncertainty in the conversion loss. The output noise from the mixer at intermediate frequencies of 20–90 MHz was measured to be 30–40 K, which in the ideal case with 7 dB conversion loss yields a DSB mixer noise between 80 and 100 K.

IV. Conclusion

Experimental data and a simple circuit model allow us to predict that HEB mixers will perform well at THz frequencies. We expect a DSB receiver noise temperature below 200 K to be realizable with 100 MHz bandwidth. Other materials, such as NbN, will allow an increase of the bandwidth to several GHz.

ACKNOWLEDGMENT

The authors thank Professors E. Gershenzon and G. Gol'tsman for fruitful discussions.

REFERENCES

[1] E. M. Gershenzon *et al.*, "Millimeter and Submillimeter Range Mixer Based on Electronic Heating of Superconducting Films in the Resistive State," *Sov. Phys. Superconductivity,* vol. 3, pp. 1582–1597, 1990.

[2] G. N. Gol'tsman *et al.*, "Sensitive Picosecond NbN Detector for Radiation from Millimeter Wavelengths to Visible Light," *Supercond. Science and Technology,* vol. 4, p. 453, 1991.

[3] F. Arams *et al.*, "Millimeter Mixing and Detection in Bulk InSb," *Proc. IEEE*, vol. 54, pp. 308–318, 1966.

[4] H. Ekström, B. Karasik, E. Kollberg, and K. S. Yngvesson, "A Microwave Mixer Using Superconducting Nb Films in the Resistive State," *1993 Int. Semicond. Dev. Res. Symp.*, 1993, pp. 475–478.