Reduced T_c Niobium Superconducting HEB Mixers

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A reduction in the mixer noise is expected when using superconductors with a lower transition temperature (T_c) since the thermal noise components of the mixer noise should scale with T_c. Also, the local oscillator (LO) power required for a diffusion-cooled device should decrease as T_c^2 when $T_{bath} << T_c$. We previously studied mixing in aluminum based hot-electron bolometers (HEBs) at microwave frequencies (~30 GHz), and observed a significant improvement in noise performance, and a reduction in LO power as predicted. However, the bias voltage range over which good mixer performance was observed was ~ 5-10 µV. These devices are thus susceptible to saturation effects, in particular output saturation. In the present work, we have investigated Nb HEBs whose T_c is lowered by applying a magnetic field. The goal is to study a case intermediate between Nb and Al, and hopefully to find properties that will allow use in practical receivers. A 15 kOe perpendicular magnetic field was applied to a Nb HEB (L=0.16 µm, W=0.08 µm, R_N=90Ω) to reduce T_c from 5.2 K to 2.4 K. The mixer noise, as inferred from the output noise and the conversion efficiency, decreased from 390 K, DSB to 171 K, DSB. The LO power required for near optimum mixer conversion efficiency (η_{mixer} = - 9 dB in this device) was 8nW in zero field, and ~ 2 nW when T_c was reduced to 2.4K. T_{bath}=0.22K. The conversion bandwidth was previously measured to be 2.4 GHz and the same bandwidth was observed in the presence of a magnetic field. By lowering T_c, the voltage range over which good mixing was observed also decreased. However, even with T_c reduced to 2.4 K, the conversion efficiency dropped by 3dB from its maximum value only when the bias voltage was changed by ~ 90 µV. Saturation effects should thus be much less of a concern in these devices than in Al HEBs. In situations where the application of a large magnetic field is not feasible, we suggest using Ta based HEBs. Ta HEBs should have T_c ~ 3-3.5K and material properties very similar to Nb.

I. Introduction

Nb and NbN hot-electron bolometer (HEB) mixers are promising for spectroscopy applications above 1 THz.[1-3] Diffusion-cooled Nb devices have been shown to have a receiver noise temperature as low as T_R=1800K at 2.5 THz, with an intermediate (IF) bandwidth of ~ 9 GHz in this same device.[1] Mixer noise performance is predicted to improve when the transition temperature (T_c) of the superconducting HEB is lowered. A reduction in the mixer noise temperature and the local oscillator (LO) power is expected.[4]

Recently, we studied diffusion-cooled HEB mixers made of Al. Low frequency studies (f_{LO} ~ 30GHz) indicate that the mixer performance is very good and in agreement with predictions.[5] In the Al devices, optimum mixer performance is observed only within a narrow range of bias voltages, ΔV ~ 5-10 µV. Al HEB tests at 600 GHz indicate that the conversion efficiency is about 10dB lower than that measured at microwave frequencies.[6] It is possible that the discrepancy between these two measurements is the result of saturation effects. For example, output saturation might be an issue if enough background radiation is down converted to create an IF voltage swing in excess of several microvolts. In Fig. 1, the mixer conversion efficiency is plotted, and it drops when broadband noise is coupled with the mixer input signal. If the frequency of the noise is such that most of it can be down converted to the IF, a significant decrease in conversion efficiency can be observed for even ~10pW ($T_{background\ noise}$ ~ 100K) of incident power.

Since the voltage range for operation for Al HEBs is small, we consider materials with a T_c that lies between 1K (Al) and 6K (Nb) for practical applications. The approach taken here was to lower the T_c of Nb HEBs by applying a perpendicular magnetic field. These devices should have a lower mixer noise temperature compared to Nb in zero field, but not as low as that obtained with Al. Yet, they should be much less prone to saturation effects. Overall, they should be more like the successful Nb HEBs. The data presented are for a local oscillator frequency of ~ 30 GHz. The motivation for these studies is that the microwave measurements allow for a more thorough exploration of the device physics than can be done with usual sub-millimeter wave measurements. In applications where a magnetic field may be difficult to generate or may interfere with other components, the use of Ta (T_c ~ 3-3.5 K) is suggested. Since Ta and Nb share many material properties,[7] it is hoped that any results obtained with reduced-T_c Nb devices can be reproduced with Ta HEBs.

II. Devices and Experimental Setup

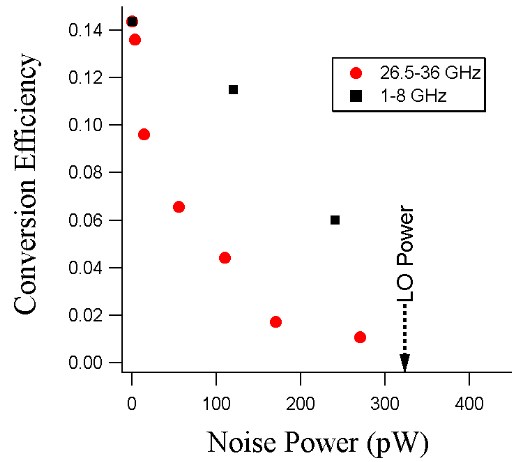

Figure 1: Conversion efficiency for an Al HEB in the presence of background noise. Based on the measured IF bandwidth and the LO frequency chosen, ~85% of the noise in the 26.5-36 GHz can be down converted to the IF.

The devices measured were 10 nm thick Nb HEBs on quartz substrates. The fabrication details of the self-aligned process used are given in Ref. 8. The data presented here are for a device with width 0.08 μm and length 0.16 μm. Thick Au pads (100 nm) are used to contact the Nb microbridge. Measurements were previously made on this device (Device B in Ref. 9) at 20 GHz by Burke, et al.[9] Also, devices from this batch and ones similar to it have been used for HEB mixer tests at ~ 600 GHz, 1.2 THz, and 2.5 THz.[1-2,10]

The device is placed on the cold stage of a variable temperature ^3He cryostat. The system described here is similar to the setup in Ref. 5, but differs in instrumentation and functionality. For convenience, all measurements were made at a bath temperature of T=0.22K, and similar mixer performance is expected even at ~ 1.5K. A magnetic field up to 50 kOe could be applied perpendicular to the sample. The LO source is a YIG oscillator

(26.5-40 GHz), and the RF signal source is the internal generator of the HP8722D network analyzer. A path is present for the injection of noise from an external source to simulate background radiation. The first stage IF amplifier is a broadband cooled HEMT. The IF signal was analyzed on a HP8593E spectrum analyzer. Output noise was measured by rectifying the IF signal using a room temperature Schottky diode detector. A block diagram and picture of the measurement setup are given in Fig. 2.

III. Results

A. I-V Curves

The T_c is measured to be 5.2 K in the absence of an applied magnetic field. The critical current is 105 µA with no LO. By applying a 15 kOe perpendicular magnetic field, T_c is reduced to 2.4 K. For this comparison, T_c is taken to be the temperature corresponding to the middle of the resistive transition. The unpumped critical current is reduced to 11 µA. In Figs. 3-4, pumped and unpumped I-V curves for T_c = 5.2 K and 2.4 K are given.

B. LO Power and Conversion Efficiency

The LO power used for mixing was chosen so as to optimize the conversion efficiency. A particular LO power was set and the bias voltage was swept to determine the maximum conversion efficiency for that pump power. The pump power was then incrementally changed to find near optimum operating conditions. Both with and without a magnetic field, the best conversion efficiency obtained was –9 dB.

The LO power required for mixing for a diffusion cooled device is predicted to be

$$P_{LO}=4\,\mathcal{L}\,(T_c^2-T^2)\,/\,R \qquad (1)$$

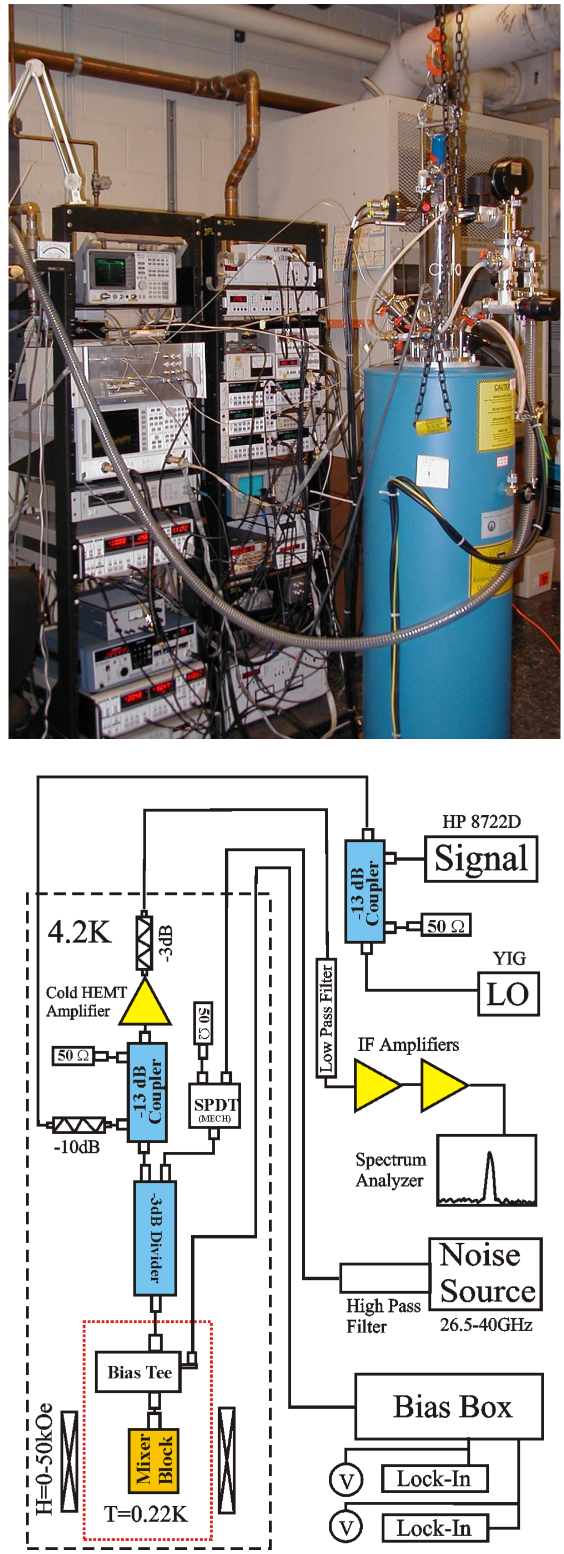

Figure 2: Measurement Setup

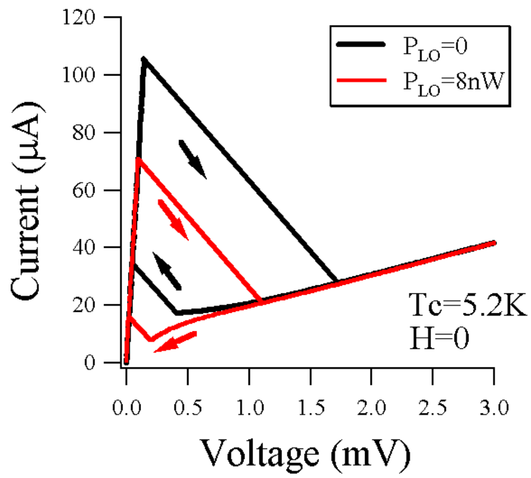

Figure 3: I-V curves in zero applied magnetic field.

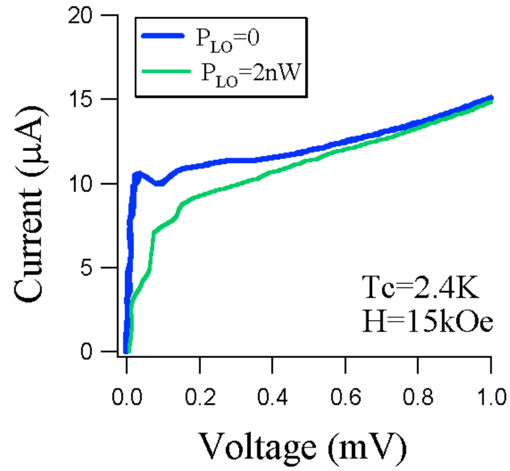

Figure 4: I-V curves in an applied magnetic field.

where L is the Lorenz constant, T_c is the transition temperature, T is the bath temperature, and R is the device resistance.[9,11] Since the bath temperature is 0.22 K, a four fold reduction is LO power is expected in this case. The LO power needed for optimum conversion efficiency with T_c=2.4 K is 6 dB lower than that with T_c=5.2K, as predicted.

C. Conversion Efficiency vs. Bias Voltage

In Fig. 5, the conversion efficiency is presented as a function of bias voltage. The bias voltage is swept from a large positive voltage down to zero. Data points corresponding to lower bias voltages where switching and/or other instabilities were observed are not shown

Both with and without a magnetic field it is possible to obtain a best conversion efficiency of –9 dB. However, the conversion efficiency varies more sharply with bias voltage when T_c is reduced. Without a field, with T_c=5.2 K, the conversion efficiency drops by 3 dB from its maximum value when the bias voltage is shifted by ~ 200 μV. In the presence of the field, the same 3dB drop now occurs when the bias voltage is shifted by ~ 90 μV. This is a considerably larger voltage range that observed with Al devices; see Table I. This Nb device, even with T_c = 2.4 K, should be much less susceptible to saturation effects than an Al HEB.

D. Mixer Noise

The mixer noise temperature is inferred from the output noise temperature and the single sideband conversion efficiency, η ($T_{M,DSB}=T_{output}/2\eta$). The thermal components of the mixer noise – Johnson noise and thermal fluctuation noise – should decrease with T_c. Such a reduction can be significant if the mixer noise is much larger than fundamental quantum noise and is dominated by thermal sources. At 30 GHz, the quantum noise limit ($T_Q=h\nu/k$) is ~ 1.4 K. The output noise when operating with maximum conversion efficiency (-9dB) decreased from 88 K to 46 K when T_c was reduced by a factor of ~ 2 from 5.2 K to 2.4 K. The corresponding mixer noise decreases approximately proportional to T_c, from 390K to 171K when T_c is 5.2K. The mixer noise increases by 3dB from its minimum value when the bias voltage is shifted by ~ 440 μV. This voltage range is smaller when T_c is 2.4K,

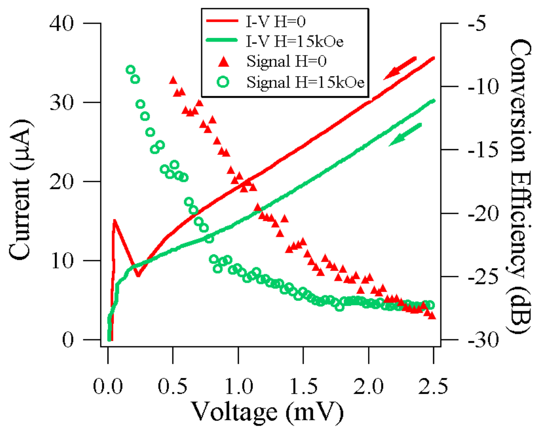

Figure 5:Conversion efficiency versus bias voltage and pumped I-V.

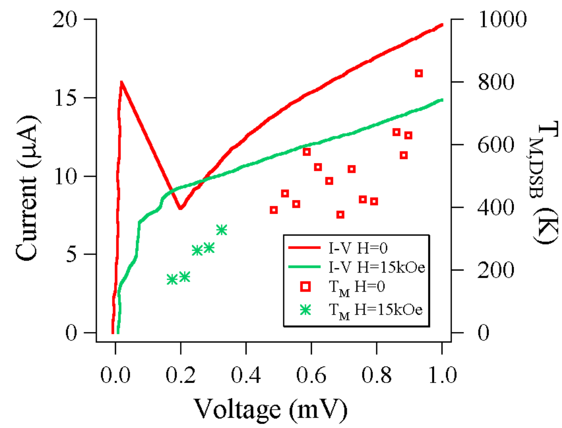

Figure 6: Mixer noise versus bias voltage and pumped I-V.

and the 3dB drop off occurs at a voltage shift of 152μV. The mixer noise as a function of bias voltage is presented in Fig. 6.

IV. Conclusions

The T_c of a Nb HEB was successfully lowered by the application of a magnetic field from 5.2 K to 2.4K. The mixing results for Nb, reduced T_c Nb, and Al HEBs are summarized in table I. The optimum conversion efficiency observed was –9dB for both values of T_c. The mixer noise temperature decreased nearly linearly with T_c. The LO power needed for optimum conversion efficiency decreased from 8nW with T_c=5.2 K to 2 nW with T_c=2.4 K, as predicted in Eq. 1. The bandwidth has previously been measured to be 2.4 GHz and was unchanged when T_c was reduced.

A 3dB drop in conversion efficiency was observed for the device for a bias voltage change of ~ 90μV. This is a considerably larger voltage range than was observed in similar studies of Al HEBs and these reduced-T_c Nb devices are much less prone to saturation effects. For example, for a 300K background and a device IF bandwidth of 10GHz, a noise voltage of ~ 20μV would be generated at the output, and thus not result in significant output saturation. Further tests are in progress to determine when input/output saturation is observable in Nb and reduced-T_c Nb HEBs, and what effects lowering T_c has on these limits. We note that the mixing data for all parameters (output noise, conversion efficiency, LO power, and DC power) obtained in zero magnetic field agree well

DEVICE	L (μm)	R_N (Ω)	P_{LO} (nW)	Conv. Eff. (η) (dB)	$T_{M,DSB}$ (K)	ΔV_{-3dB} Conv. Eff. (μV)	ΔV_{-3dB} Mixer Noise (μV)
Nb (T_c=5.2K)	0.16	90	8	-9	390	200	440
Nb (T_c=2.4K)	0.16	90	2	-9	171	90	152
Al (T_c=1.0K)	0.60	52	0.5	-8	4	~5	~5

Table I: Microwave mixing performance for Nb, reduced T_c Nb, and Al HEBs. The Al data is for device A in Ref. 5. The last two columns give the shift in bias voltage required to produce a 3dB degradation in the conversion efficiency and mixer noise temperature.

with previous microwave measurements ("optimum gain" case, Ref. 9).

Finally, Ta (T_c ~ 3-3.5 K) devices need to be fabricated and tested to see if the results reported here can be reproduced in those devices. Those devices would be used in receivers where a large magnetic field would be impractical.

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