Detailed Characterization of Quasi-Optically Coupled Nb Hot Electron Bolometer Mixers in the 0.6-3 THz Range

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Abstract

Two type of Nb diffusion-cooled HEB mixers have been studied. One uses a twin-slot antenna designed for 700 GHz, and has a bridge length of 200 nm. This device is fabricated using an *in situ*-process for the interface between the bridge and the cooling pads. An uncorrected receiver noise temperature of 1200 K at 640 GHz and an IF bandwidth of 5 GHz have been measured. The second device uses a log-periodic antenna designed for a wide RF bandwidth. However, there is a misalignment of the Nb bridge with respect to the Au cooling pads. Receiver noise temperatures at 0.64, 1.9, and 2.5 THz have been measured. We are able to link the geometry feature to the measured properties.

1. Introduction

Superconducting Nb diffusion-cooled hot electron bolometer mixers have shown promising performance such as high sensitivity, large intermediate frequency bandwidth, and low local oscillator power. They are the most promising mixers for frequencies beyond 1 THz. Several research groups[1-5] are working on such devices and report good performance. However, extensive experimental data concerning the RF performance is still lacking. It is believed that the difficulty comes from the fact that the performance of such devices is very sensitive to the fabrication processing steps, the detailed geometry, and the test environment. In this work, we show that by changing one fabrication step defining the interface between the Nb bridge and Au cooling pads in-situ, good performance in terms of IF bandwidth and sensitivity can be achieved. We will also show that the DC and RF performance can strongly depend on the device geometry, as observed from a device having a misalignment of the bridge with respect to its cooling pads.

2. Mixers

Two type of quasi-optical mixer designs have been explored in this work. One uses a twin slot antenna in combination with transmission line (CPW) for 700 GHz and 2.5

THz[5]. Although the final goal is to develop devices operating at 2.5 THz, unfortunately, only those designed for 700 GHz work from two batches using a new fabrication process that will be described shortly. Details of the device *IS 1_2 G4* are listed in Table 1. An SEM micrograph of a similar device is shown in fig. 1.

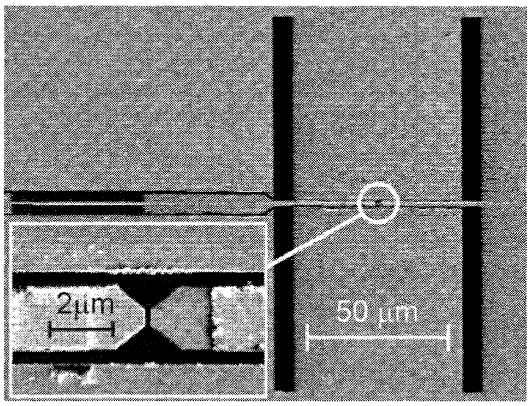

Fig. 1 SEM micrograph of a quasi-optical Nb HEB mixer with a twin-slot antenna, designed for 700 GHz. The device is similar to IS 1_2 G4. The inset shows a zoom of the CPW/bridge area.

Table 1. Details of device IS 1_2 G4. L, w and s are the antenna slot length, width and separation, respectively. a and b are the slot-- and center line width in CPW transmission lines. $Z_{hi,low}$ are filter sections having high and low impedance.

frequency	0.7 THz
Antenna	twin slot, L=137μm, w=6.9μm , s=68.5μm, metal Au layer: 300nm
CPW line	a=1.2 μm, b=2.0 μm
Filter	Z_{low}: a=1.2 μm, b=6.6 μm, Z_{hi}: a=3.9 μm, b=1.2 μm
Nb bridge	Thickness = 14 nm, length = 200 nm, width = 250 nm (nominal)
Resistance	R_{10K} = 40 Ω, R_{4K} = 7 Ω (series R) , R_{300K} = 104 Ω
Substrate	Si, 300 μm thick, one-sided polished (not on purpose)

The second type of mixer is based on a log-periodic antenna (2×15 teeth), which should have a wide RF bandwidth. The antenna has a self-complimentary design and its impedance is relatively high. Since the Nb devices usually have a low impedance, there is always a considerable mismatch between the antenna and the bolometer, causing degradation of noise performance. So such a antenna is not the optimum choice for the HEB to obtain the maximum performance. However, the wide band allows us to verify the frequency dependence of the HEBM sensitivity. The SEM micrograph of the device reported in this work is shown in fig. 2. It is important to note that there is a misalignment of the bridge with respect to the cooling pads (about 150~nm), that is partly due to an error in the e-beam lithography and partly due to the fact that this device is designed for having a narrow cooling pads. The relevant parameters are; 300 nm separation between the cooling pads, 400 nm Nb bridge width, 22 Ω normal state resistance.

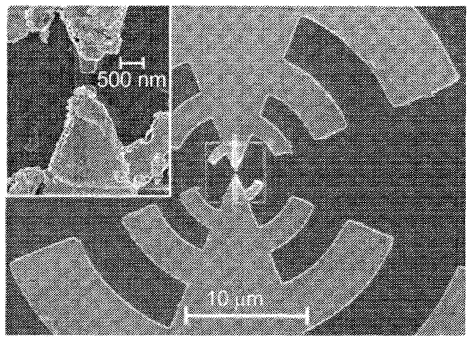

Fig. 2. SEM micrograph of device IS 1_4 F3. The inset shows the Nb nanobridge contacted by Au cooling pads. The length and width of the bridge are 300 nm and 400 nm, respectively. Clearly, the bridge is misaligned with respect to the cooling pads.

3. Fabrication.

The fabrication process is different from the one described in ref. 5, in essentially two aspects. a) the interface between the Nb bridge and Au cooling pads is realized in situ, so no vacuum breaking. This is realized by depositing thin Nb and a thin Au cap layer in situ. After defining the Au cooling pads, the Au cap layer will be etched away; b) we use a thin Al strip as an etching mask to define the bridge width.

4. RF measurement set-up

The noise temperature measurements are performed by a standard Y-factor technique with 300/77 K loads in the receiver signal path. All measurements are taken at an IF of 1.4 GHz . We use a Mylar beam splitter with a thickness of 15 μm to couple the LO into the mixer. A number of BWOs and Carcinotrons covering the frequency range from 0.3 to 1.2 THz serve as a local oscillator. Above 1 THz an optically pumped FIR ring laser in our lab is used. The output lines at frequencies of 1.6 THz, 1.9 THz and 2.5 THz are now available.

IF bandwidth measurements are done using a pair of submillimeter sources at frequencies around 650 GHz. A Miteq 0.1-8 GHz cryo-amplifier is used as the first stage amplification. It is followed by a room temperature amplifier and further by a spectrum analyzer.

5. Measurement results of a twin-slot antenna coupled HEB mixer designed for 700 GHz

5.1 DC measurements

We start with a twin slot antenna-coupled device labeled as IS 1_2 G4. The critical temperature T_c of the Nb nanobridge is 7.4 K, which equals to the larger films on the same wafer. The T_c of the Nb under the Au cooling pads (110 nm thick) is 6.2 K, thus the difference between the two T_c amounts to 1.2 K. This difference is nearly the largest observed so far in our Nb HEBMs, indicating a strong suppression of superconductivity by the Au cooling pads due to the proximity effect[6]. So one can expect a Nb/Au interface with a high transmissivity. Both the high transparent interface and the strong suppression of superconductivity of the Nb under the cooling pads are favorable for diffusion cooling. The critical current I_c is 160 μA at 4.2 K and increases to 260 μA at 3.2 K. The normal state resistance R_N measured above T_c is 40 Ω (as given in table 1), which is higher than expected. Based on the nominal geometry and square resistance measured in a larger structure, we expect the value to be around 12 Ω. We suspect that the deviation from the nominal value is partly due to over-etching while defining the Nb nanobridge. This may cause the bridge to be narrower than the nominal size. However, since SEM micrograph of this particular device is not available, we cannot make a hard conclusion. The serious resistance of 7 Ω is due to the filter structure.

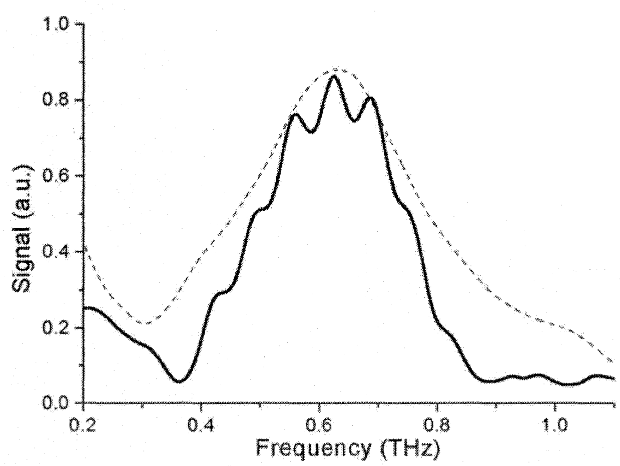

Fig. 3. Measured direct response of a twin slot antenna coupled Nb HEB mixer. The thick line gives measured data and the thin line indicates the simulation.

5.2 Direct response

Fig. 3 shows the direct response of the device as measured by FTS. The thick solid line indicates the measured curve. We calculate the FTS response for this specific device (real geometry) using the model described in ref. 5. The result is shown as a dashed line in Fig. 3. This curve includes the effect of all the optics, so we can compare it directly to the measurement. The peak frequency is well explained, however, the measured bandwidth is ~20% smaller than the predicted one. It is worthwhile to mention that other samples from the same batch show a better agreement. So it depends strongly on device differences. We present however the data from this device because it is completely characterized regarding its noise and IF bandwidth.

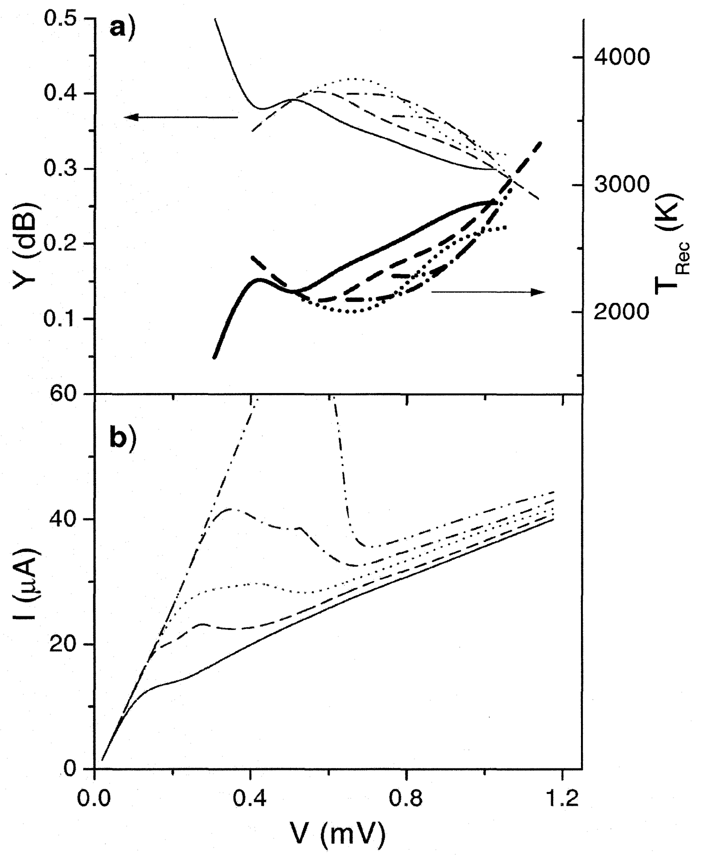

Fig. 4. In the upper panel, Y-factor (thin lines) and T_{rec} (thick lines) vs bias voltage for the device IS 1_2 G4 with several LO levels at 0.64 THz; in the lower panel, corresponded pumped IV curves are also given. The correspondence is indicated by the line style, e.g. all the dashed lines have the same LO power. These data are taken at 4.2 K.

5.3 Receiver Noise Temperature

The Y-factor and thus the receiver noise temperature of the same device(IS 1_2 G4) have been systematically measured as a function of bias voltage for different LO power levels at the bath temperatures of 4.2 and 3.2 K. Fig. 4 shows the Y-factor and the deduced receiver noise temperature as a function of bias voltage at four different pumping levels, together with their corresponding pumped IV curves, taken at a T_{bath} of 4.2 K. At this temperature, the best Y-factor of 0.5 dB has been measured manually (not included in the figure), corresponding to a receiver noise temperature of 1600 K (DSB). Note that all noise figures given in this paper have not been corrected for any loss in the signal path, e.g. beam splitter.

We now try to look at this result more closely. Two features are worthwhile to mention. First of all, for a given bias voltage, e.g. at 0.8 mV, T_{rec} decreases with increasing LO power (means starting from less pumped IV curves), passes a minimum and eventually increases again. Secondly, for a fixed LO power, T_{rec} has a minimum between low and high voltages. So these features clearly demonstrate that there is a region where the mixer has the lowest noise if one adjusts LO power and the bias voltage. Such features have been reported in NbN phonon cooled mixers[7], but rarely reported in Nb mixers. Furthermore, the highest Y-factor does not occur at the lowest bias voltage, at which the dynamical resistance starts to be negative, that is favorable for the real application. The LO power absorbed by the mixer for the case of the lowest noise is estimated to be 30 nW.

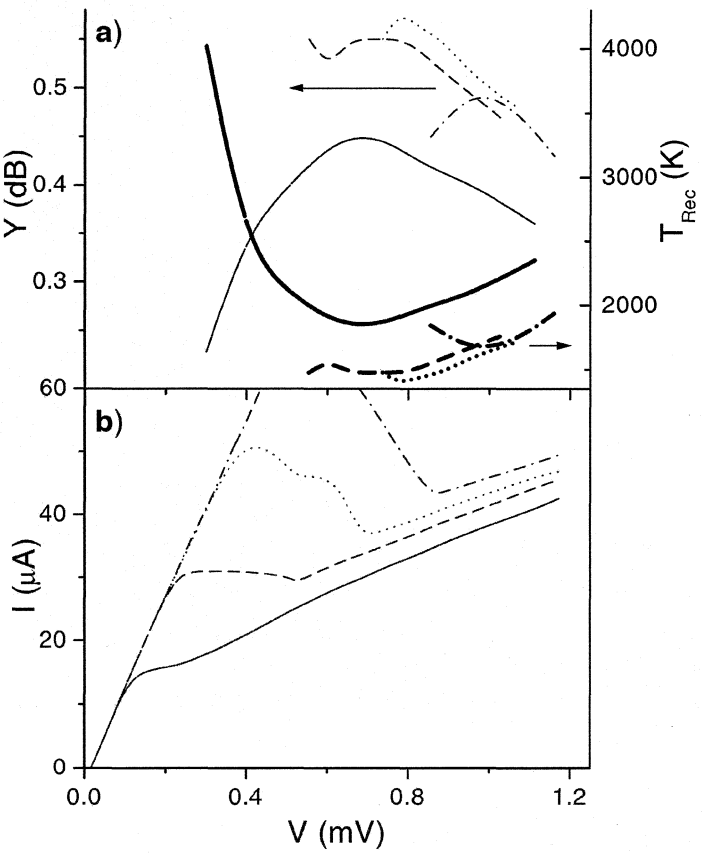

Fig. 5. In the upper panel, Y-factor (thin lines) and T_{rec} (thick lines) vs bias voltage for the same device as in fig. 4 with several LO levels at 0.64 THz. in the lower panel, corresponded pumped IV curves are also given. The correspondence is indicated by the line style, e.g. the dashed lines mean the same LO power. These data are taken at 3.2 K.

We repeated the measurement by lowering the bath temperature to 3.2 K. The result is given in fig. 5. In general, we see similar behavior of Y-factor vs the bias voltage for different LO powers. However, overall Y-factor increases at this temperature. Now the highest Y-factor goes up to 0.65 dB (not included in the figure). This gives a receiver noise temperature of 1200 K. We also notice that it requires in general more LO power to pump the device.

The best receiver noise temperature decreases by ~26 % upon decreasing the temperature to 3.2 K. Similar improvement has also been observed in our waveguide Nb HEB mixers and by other groups. Attempts have been made to understand whether this is due to an increase of mixer gain or a decrease in mixer output noise[8]. Unfortunately, the issue is still not fully resolved.

We also measure the receiver gain in order to determine the mixer gain. The IF output power of the device has been measured by changing hot/cold loads. We find the maximum DSB receiver gain to be -20 dB. Using Table 2, which summarizes all other losses in the receiver, we deduce a DSB mixer gain G_{Mix} to be –16 dB. We can only present the mixer gain at 4.2 K, but not at 3.2 K since in the latter case no such IF power data have been recorded.

Although there is no well-established model to predict the mixer gain of a diffusion-cooled mixer, for curiosity, we calculate this value by using the electronic hot-spot model[8,9] with inputs of the experimental IV curves and the device parameters. We find the maximum mixer gain to be –12 dB. So, the difference is not considerably large.

Table 2. Balance of the receiver losses at 0.64 THz, including also a loss due to a slight off from the antenna peak frequency. We did not include the effect of roughness on one side polished substrate.

Elements	Loss(dB)
Splitter	0.4
Window	1.0
Zitex filter (x2)	0.2
Lens (reflection)	1.5
Lens (absorption)	0.3
Antenna offset	0.2
One side-polished Si	?
Total	3.6

5.4 IF bandwidth

The IF bandwidth of an HEBM is an important practical parameter, which is defined as the frequency at which the conversion gain drops by 3 dB. We measure this bandwidth for the same device (IS 1_2 G4). We start with a low bias voltage (0.65 mV), at which the minimum noise temperature has been obtained. The conversion gain as a function of IF frequency is presented in fig. 6. The one-pole Lorentzian fit to the data gives the IF bandwidth of 3.2 GHz. By increasing the bias voltage to a high value (~ 3mV), we repeat the measurement and find the IF bandwidth of 4.5 GHz. Several other devices with the same bridge length from the same batch have been evaluated, showing the IF bandwidth to be in a range of 4-5 GHz at high bias voltages. An example is given in fig. 7. This is measured in another device labeled as IS 1_2 B9 and the bandwidth is 5 GHz. To make a comparison, the data from a similar device but produced by non in-situ process is also included. For this device, the IF bandwidth obtained is only 2 GHz.

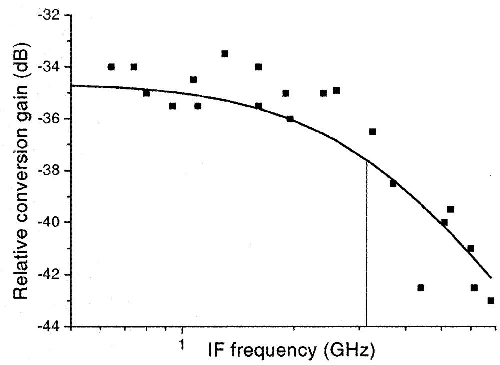

Fig. 6. The measured relative conversion gain as a function of IF frequency for the device (IS 1_2 G4) at a bias voltage of 0.65 mV for which the best sensitivity was obtained (in the optimal bias point). The one-pole fit gives a roll-off frequency of 3.2 GHz. This device has a nominal length of 200 nm.

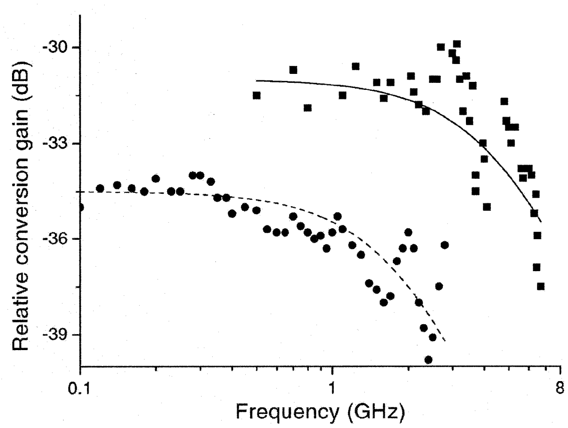

Fig. 7. The relative conversions gain as a function of IF frequency, measured on a device (IS 1_2 B9) made in-situ (squares) and one made ex-situ ES 2_2 (dots). The nominal bridge length for the both devices is 200 nm. The in-situ device gives an IF bandwidth of 5 GHz and the other one 2 GHz.

In general IF bandwidth of such a device should increase with increasing the bias voltage[10]. This is because at low bias voltages, only a part of the superconducting bridge is driven to be normal. At high bias voltages one can view the superconducting bridge just as a metallic strip. So the IF bandwidth should increase and approach to what predicted by the diffusion-cooling expression:

$$IF_{roll\text{-}off} = \pi D / 2L^2$$

where D is the diffusion constant and L the bridge length. We calculate this value by taking the nominal length 200 nm and using a diffusion constant of 2.1 cm^2/s, which is deduced from a value measured in thin Nb film[8], taking the sheet resistance of our film into account. Using these values, we find the IF bandwidth of 8.3 GHz, which is higher than the observed one.

5.4. Discussions

We have evaluated three similar devices in the RF setup and obtained very similar noise performance. The noise figure presented in this paper is the lowest among the tested quasi-optical mixers in our lab. They are in general better than the devices produced in the non in-situ fabrication process. Unfortunately we can only compare the data at 640 GHz, but not at 2.5 THz because we did not have devices designed for 2.5 THz using the new process. To have a comparison, we also summarize sensitivity measurements based on devices produced by the non in-situ process. Several batches of the devices have been produced and a considerable amount of them have been tested in order to evaluate the noise performance. The DSB noise temperatures vary between 1.500-2.000 K at 640 GHz and 4.500-10.000 K at 2.5 THz. These data have not been corrected for the losses in the signal path, which we estimate to be about 4-5 dB (beamsplitter, dewar window and reflections at the air/Si lens interface).

Can we further improve the sensitivity? There must be room for if we simply compare to the best result obtained in the waveguide mixers in our lab, that was 900 K (uncorrected) at 700 GHz [8]. In order to push the noise temperature further down, more specifically the following aspects need to be improved. a) our Si lens does not have any anti-reflection coating. This gives rise to a 1.5 dB loss due to reflections from the lens surface; b) our dewar window is optimized for 2.5 THz. An improvement of about 0.4 dB can be made in optimizing the dewar window for 0.7 THz; c) This particular batch is produced on single-sided polished Si substrate. The backside has an RMS roughness of about 20 μm, being a considerable fraction of the wavelength. This can give a negative contribution to the sensitivity measurement, but it is hard to be quantified; d) The bath temperature of 3.2 K is still not lower enough.

6. Measurement results of a log-periodic antenna coupled HEB mixer designed for a wide RF band

In this section, we will summarize the key measurement data from the log-periodic antenna coupled device (IS 1_4 F3). The motivation to present such data has two folds. 1) this is one of very few devices in which we can perform systematic measurements such as DC characterization, FTS, Y-factor and the gain as a function of bias with different LO powers, and also IF bandwidth. For this device, we could in the end take the SEM micrograph; 2) we see the correlation between the measured properties and its geometric anomaly.

Here are the key observations from this device:

- Resistance vs temperature curve has additional structure, differing from a well-defined HEB device
- Un-pumped and in particular pumped IV curves differ pronouncedly from the calculated curves using the electronic hot-spot model.
- The IF bandwidth has only 0.8 GHz, which is much smaller than 4 GHz, as expected for a separation of cooling pads (300 nm) and the diffusion constant. The relative conversion gain vs IF deviates from the Lorentzian behavior.
- For the optimized operation, this device requires a LO power of 100-150 nW, which is 1.5-2 times more than a usual Nb HEB mixer. This suggests that LO power is not only absorbed in the Nb between the cooling pads, but also the Nb next to them.

Apart from those observations, we study the FTS response, which starts from 0.3 THz to 3 THz, confirming that it is indeed a wide band receiver. We also measure Y-factor and thus DSB receiver noise temperature at 0.64, 1.9 and 2.5 THz. Those values together with the mixer noise temperature and mixer gain estimated from the balance of receiver losses are listed in table 3. Note these noise data are certainly not the best if we compare them to the data given in section 5.4.

Table 3. The Y-factor and receiver noise temperature (DSB, uncorrected) of a log-periodic antenna coupled Nb HEB mixer at three different frequencies. The estimated mixer properties are also given. T_{Mix}, G_{Mix} , and G_{opt} are the mixer noise temperature, mixer gain, and the gain of the optical signal path, respectively.

f (THz)	Y-factor	T_{rec}	T_{mix}	$G_{mix}(dB)$	$G_{opt}(dB)$
0.64	0.35	2400	600	-12.7	-6.8
1.9	0.13	6900	920	-11.8	-7.1
2.5	0.10	8900	900	-12	-9.0

7. Conclusions

In conclusion, we have designed and fabricated quasi-optical Nb diffusion-cooled HEBMs to operate in the frequencies up to 2.5 THz. The IF bandwidth of the devices with a 200 nm long bridge produced using the in-situ fabrication process is as high as 5 GHz. The best receiver noise figure is 1200 K at 640 GHz. Through the systematic measurements we have confirmed that Nb HEB mixers in principle work and demonstrated reasonably good performance. However, we emphasis that the detailed fabrication process steps and also the device geometry can affect the overall performance. Unresolved problems in our case are a good control over fabrication process with respect to both reproducibility and yield.

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