Direct comparison of the sensitivity of a spiral and a twin-slot antenna coupled HEB mixer at 1.6 THz

J.R. Gao, M. Hajenius, Z.Q. Yang, T.M. Klapwijk, W. Miao, S. C. Shi, B. Voronov, and G. Gol'tsman

***Abstract*— To make a direct comparison of the sensitivity between a spiral and a twin-slot antenna coupled HEB mixer, we designed both types of mixers and fabricated them in a single processing-run and on the same wafer. Both mixers have similar dimensions of NbN bridges (1.5-2 μm×0.2 μm). At 1.6 THz we obtained a nearly identical receiver noise temperature from both mixers (only 5% difference), which is in a good agreement with the simulation based on semi-analytical models for both antennas. In addition, by using a bandpass filter to reduce the direct detection effect and lowering the bath temperature to 2.4 K, we measured the lowest receiver noise temperature of 700 K at 1.63 THz using the twin-slot antenna mixer.**

***Index Terms*—Hot electron bolometer mixer, twin-slot antenna, spiral antenna, and THz.**

I. Introduction

Spiral antennas are extremely useful for laboratory tests to evaluate HEB mixers at different frequencies because of the broad RF bandwidth as a result of a non-resonating frequency response. However, such antennas have a circular polarization, so they are less favorable for actual applications in a telescope. In contrast, twin-slot antennas are resonant ones with a linear polarization and an acceptable beam pattern. Therefore they are more desirable for real applications. Because of the resonant type of antenna, to reach the maximum RF coupling at a designed frequency the impedance matching between antenna and HEB is more important. This is partly due to the fact that the theoretical design model has not been fully developed for THz frequencies and partly due to the fact that the bridge impedance should be under good control during the fabrication.

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Spiral antenna coupled NbN HEB mixers tend to show lower receiver noise temperatures than reported for twin-slot antenna mixers. However, there has so far been very few work dedicated to a direct comparison between these two types of antenna coupled mixers [1]. Such a comparison turns out to be difficult. One of the reasons is that, due to different antenna geometries and corresponding fabrication recipes, it is very challenging to fabricate both types of mixers in a single wafer and a single processing-run in order to make a sensible comparison. Here we report a direct comparison of the heterodyne sensitivity at 1.6 THz using two types of mixers fabricated on the same wafer with the same process.

II. Theoretical considerations of the heterodyne sensitivity

The DSB receiver noise temperature T_{rec} of a HEB mixer reflects the effective noise temperature and gain of the cascade of the RF optical components, mixer, and IF (amplifier) chain, and is given by

$$T_{rec} = \left(T_{RF} + \frac{T_{Mix,SSB}}{2G_{RF}} + \frac{T_{IF}}{2G_{RF}G_{Mix,SSB}} \right) \qquad (1)$$

where T_{RF} and G_{RF} are the equivalent noise temperature and gain of the RF optics, respectively. $T_{Mix,SSB}$ and $G_{Mix,SSB}$ the SSB mixer noise temperature and gain, and T_{IF} the noise temperature of the IF chain. In practice, the RF power coupling between antenna and HEB detector is not 100%, thus there will be an additional loss term added into the G_{Mix} or G_{RF}. Furthermore, if the DC resistance of the HEB at the operating point is different from the input impedance (50 Ω) of IF amplifier, there will be impedance mismatching between the HEB and IF amplifier. Consequently, this will reduce the mixer gain and thus increase the receiver noise temperature [2,3]. It becomes obvious that, to compare the sensitivity of two types mixers due to different antennas, ideally one needs the exact same HEB devices, which can guarantee the same mixer noise temperature, gain, and IF impedance. As discussed in the next section, the input impedances of two antennas are not the same. Hence, it is unrealistic to use the exact same device size, which determines the impedance. In this work, we choose HEBs that are essentially identical, but slightly different in widths in order to satisfy the RF impedance matching.

III. HEB MIXERS

Mixers used are phonon-cooled HEBs based on a standard NbN film of about 5.5 nm on a Si substrate [4] which is sputtered grown at MSPU, Moscow. It has a superconducting critical temperature of 10 K. For the fabrication, we use a similar process as described in ref.[5] for both types of mixers except for a new fabrication step for both antenna structures. All devices are made on the same wafer. The DC resistance versus temperature data of HEBs from this batch, together with the earlier RF measurements of similar batches, suggests that the reproducibility in the performance among different HEBs is excellent (~10 %).

A. *Spiral antenna mixer*

We start with a mixer that is coupled to a self-complementary spiral antenna. It is similar to what used in our previous work [6]. The detailed antenna structure is illustrated by the SEM micrograph in Figure 1, in which the bolometer locates in the center of the antenna and has a width of 2 μm and a length of 0.2 μm. The ratio of length and width, together with the sheet resistance of the film, defines the normal state DC resistance, which is 96 Ω (at low temperatures) and is in our case assumed to be same as the RF impedance.

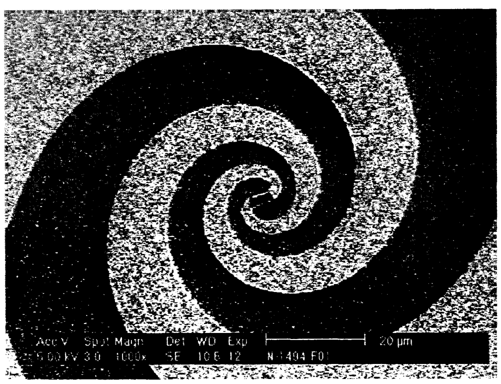

FIG. 1 SEM micrograph of a self-complementary spiral antenna coupled HEB mixer on Si substrate. The NbN HEB has a width of 2 μm and a length of 0.2 μm, giving a low temperature normal state resistance of 96 Ω. The dark part in the center is a remaining e-beam resist, which is used to define the width of the HEB.

The feed impedance of this spiral antenna has been simulated using HFSS. We made an attempt to simulate the feed impedance by taking the Si substrate with an actual thickness (340 μm) using HFSS. We failed to complete the simulation because of the existence of surface waves in the substrate due to the fact that the substrate is electrically larger in comparison with the spiral antenna. To eliminate the surface waves, we apply the Perfectly Matched Layer (PML) method [7]. This provides a reflectionless interface between the PML layer and the substrate at all incident angles, where the surface waves are suppressed. Figure 2 shows the calculated feed impedance of the spiral antenna on a Si substrate of 10 μm at frequencies around 1.6 THz. Although in this calculation we used a thickness of 10 μm, this result should be valid for the actual device. We find 88.6 Ω for the real part of the impedance and only –3.3 Ω for the reactance, which is consistent with what calculated using the textbook analytical expression for the impedance. Having known the impedances of the antenna and the HEB, we calculate the power coupling efficiency from the antenna to the HEB and find it to be nearly 100% around 1.6 THz. In the impedance simulation, we assume a zero thickness of the metal layer and neglect any resistive loss. Furthermore, we also neglect the effect of the main beam efficiency [8] in estimating the coupling efficiency.

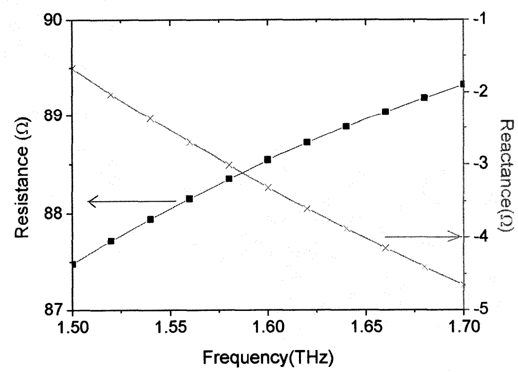

FIG. 2. Simulated feed-impedance of a self-complementary spiral antenna on a Si substrate using HFSS. To suppress the surface waves, we have to apply the Perfectly Matched Layer (PML) method. The device simulated is identical to the one shown in figure 1.

B. *Twin-slot antenna mixer*

The twin-slot mixer used is illustrated by the SEM micrograph in figure 3. The bridge has a width of 1.5 μm and a length of 0.2 μm, which results in a normal state DC resistance of 130 Ω at low temperatures. The antenna is designed for the center frequency of 1.6 THz and has the following dimensions: the slot length L is $0.30\lambda_0$ with λ_0 (=187.5 μm) the free space wavelength. The slot separation S is $0.17\lambda_0$, the slot width W is 0.07L. The CPW transmission line used to connect the two slots to the HEB has a central line width of 2.8 μm and a gap of 1.4 μm, yielding a characteristic impedance of 51 Ω [9]. The RF filter structure consists of three sections each consisting of one high-(70 Ω) and one low-impedance (26 Ω) segment, all of which are quarter wavelength long. Applying the same approach in ref. [8], we calculate a real impedance of 44 Ω for the twin-slot antenna, while a reactance of only -0.6 Ω. The CPW transmission line transforms the antenna impedance to the feed impedance of 116 Ω as the real part and 9 Ω as the imaginary. We find a power coupling efficiency of 90 % for this mixer if we take the main beam efficiency into account, but nearly 100 % if we ignore the effect of main beam efficiency. Note that in this calculation we also neglect resistive loss. In essence, despite of the different antennas, the power coupling efficiencies for both mixers are identical.

IV. Heterodyne Measurement Results

Both mixers were characterized in the same RF test setup as shown in figure 4. As local oscillator, we apply a gas laser operating at a frequency of 1.63 THz. We first characterize both HEB mixers using a non-optimal RF setup, in which a Si lens without anti-reflection coating is used and two Zytex heat filters are mounted at 4 K and 77 K behind the HEB cryostat window. In this case, RF loss in the optical path for the hot/cold load is -4.5 dB

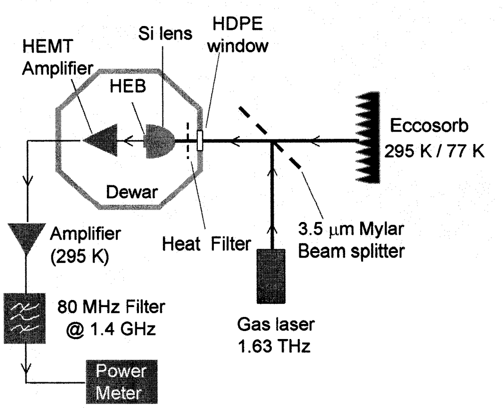

FIG 4. Heterodyne test setup used for the measurements in figure 5.

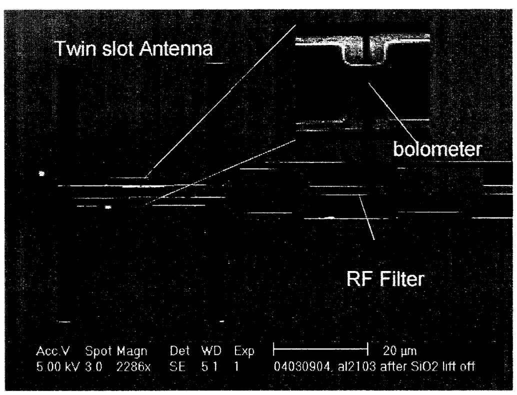

FIG. 3. SEM micrograph of a twin slot antenna coupled NbN HEB mixer (the upper figure). The bright area is covered with metal Au layer, while the dark area is the Si substrate. Between the two slots, there is a CPW transmission line that connects the slots to the superconducting bridge. In the middle of the CPW line, the HEB is located. The RF filter structure is shown in the right side of the micrograph. The NbN bridge is 1.5 μm in width and 0.2 μm in length, resulting in a normal state DC resistance of 130 Ω at low temperatures. The inset shows the zoom of the bridge area.

Figure 5 shows DSB receiver noise temperatures together with pumped IV curves measured for both HEB mixers. For the spiral mixer, the minimum T_{rec} is 1090 K found at a bias voltage of ~0.6 mV and the optimal LO power of 350 nW. The latter is determined using the isothermal technique. For the twin-slot mixer, the minimum T_{rec} is 1020 K at a bias voltage of 0.8 mV and the optimal LO power of 305 nW. The twin-slot device gives a 5 % lower noise temperature. However, this difference is comparable to the uncertainty of the measurement and thus we conclude that there is no real difference in the sensitivity at 1.6 THz between two different mixers. This result is actually a bit surprising because there are two additional factors, which might cause a difference in the sensitivity. The first one is the direct detection effect due to broadband hot/cold load blackbody radiation occurred at the Y-factor measurement [10]. One would expect a more direct detection effect in the spiral mixer because of its wider RF bandwidth. This effect, based on the measurement of a comparable spiral device, would give an increase of <10% in the noise temperature using the standard Y-factor method. The second is the difference in the resistance of the HEBs at operating point, which will influence the mixer gain [3]. The twin-slot device due to a high resistance should have better impedance matching to the amplifier. Apparently these two effects do not contribute a substantial difference in the sensitivity.

To determine the ultimate receiver noise temperature of such mixers, we replaced the lens with an anti-reflection coated one and removed also the Zytex filters to reduce RF loss. In addition, we added a bandpass filter (200 GHz bandwidth centered at 1.6 THz [11]) at 4.2 K cold plate to reduce the direct detection effect. In this case the RF loss is reduced to –2.8 dB. We measured a T_{rec} of 700 K in the twin-slot mixer (without any corrections of the optical loss) and a SSB mixer gain of –6.4 dB at a DC bias voltage of 0.7 mV and the optimal LO power of 330 nW. The value of 700 K was obtained at a reduced bath temperature of 2.4 K and is 10 % lower than what found at 4.3 K. Note this sensitivity is same as our earlier result using a twin-slot mixer, but after annealing the device in vacuum [12]. Besides, we find that a reduction of the output noise of the mixer causes the decrease of T_{rec} at 2.4 K after comparing the mixer gains and output noises at two different temperatures. In this case,

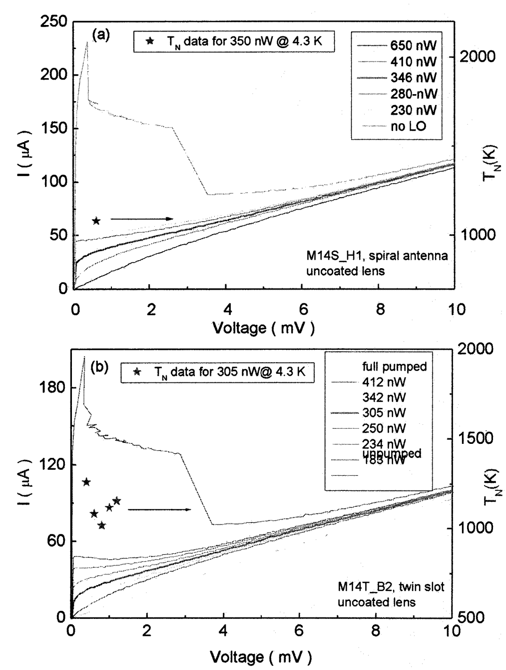

FIG.5. Current-voltage characteristics (full lines, left axis) of a NbN HEB mixer without and with radiation from the QCL at 1.6 THz. The measured receiver noise temperature T_{rec} (symbols, right axis) versus the bias voltage for the optimal LO power at the HEB. (a) for the spiral antenna mixer, while (b) for the twin-slot mixer.

the mixer gain and the output noise are -6.1 dB and 209 K, respectively, at 4.3 K, and -6.4 dB and 158 K at 2.4 K.

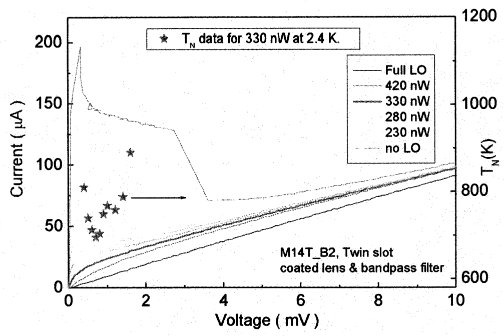

FIG 6. Current-voltage characteristics (full lines, left axis) of the twin slot antenna coupled NbN HEB mixer without and with radiation from the QCL at 1.6 THz. The receiver noise temperature T_{rec} (symbols, right axis) versus the bias voltage for the optimal LO power at the HEB, which was measured at a reduced bath temperature of 2.4 K and with an additional bandpass filter centred at 1.6 THz.

V. Conclusions

By comparing the receiver noise temperatures of two similar HEB mixers either using a spiral or a twin-slot antenna, we find that they have a very comparable sensitivity, suggesting that there is no real difference in the RF power coupling efficiency of the antenna at 1.6 THz. The result is in a good agreement with the calculated one based on semi-analytical models for both antennas. Furthermore, by reducing the direct detection effect and by reducing the bath temperature, we measured a receiver noise temperature of 700 K using the twin-slot mixer, which is the lowest at this frequency.

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