Corrigendum: Balanced superconductor–insulator–superconductor mixer on a 9 μm silicon membrane

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We would like to indicate a typographic error in equation (1) of our paper [1]. The equation should read

\[
\frac{1}{2\pi} \arctan \left[ \frac{Z_0/Z_{ms}}{(Z_0/Z_{ms})^2 + Z_0/Z_{ms} + 1} \right]^{1/2},
\]

(1)
as it appears in the original paper [2]. The statement of the further text is correct and remains unaffected by this change.

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Abstract
We present a 380–520 GHz balanced superconductor–insulator–superconductor (SIS) mixer on a single silicon substrate. All radio-frequency (RF) circuit components are fabricated on a 9 µm thick membrane. The intermediate frequency (IF) is separately amplified and combined. The balanced mixer chip, using Nb/Al/Al₂O₃/Nb SIS junctions, is mounted in a tellurium copper waveguide block at 4.2 K using Au beam lead contacts. We find uncorrected minimum receiver double-sideband noise temperatures of 70 K and a noise suppression of up to 18 dB, measured within a 440–495 GHz RF and a 4–8 GHz IF bandwidth, representing state-of-the-art device performance.

(Some figures in this article are in colour only in the electronic version)

1. Introduction
Astronomical discoveries as well as better insight into already known astronomical phenomena are often accompanied by new or improved detector technologies [1].

In the submillimeter (sub-mm) regime the implementation of superconductor–insulator–superconductor (SIS) heterodyne mixers as replacement for earlier semiconductor (Schottky) mixers has resulted in receivers with a sensitivity of a few times the quantum limit. Further improvement of observation efficiency is achieved by using SIS mixers in focal plane arrays.

Balanced superconductor–insulator–superconductor (SIS) heterodyne frequency mixers are advanced devices for receivers in the sub-mm regime. They provide a separate local oscillator (LO) port, useful for building arrays, do not limit the intermediate-frequency (IF) bandwidth by optical diplexing and suppress LO amplitude (AM) noise and thermal noise incident at the LO port [2].

Chattopadhyay et al [3] realized an integrated quasi-optical balanced mixer with a double-sideband (DSB) receiver noise temperature $T_{\text{rec, DSB}} = 105$ K at 528 GHz and an IF bandwidth of 0.5 GHz in 1999. In 2000, Kerr et al [4] reported an integrated waveguide-coupled 200–300 GHz balanced mixer on a quartz substrate with an IF bandwidth of 1–2 GHz. Between 225 and 300 GHz the authors measured the receiver noise temperature and the noise suppression. They obtained $T_{\text{rec, DSB}} = 46–78$ K and the noise suppression was better than 12 dB over the measurement bandwidth. In 2008, Serizawa et al [5] published results of a 400–495 GHz waveguide branch-line balanced mixer with $T_{\text{rec, DSB}} = 55–120$ K and an IF bandwidth of 4–8 GHz. At the Caltech submillimeter observatory (CSO), four waveguide branch-line balanced mixers covering the 180–720 GHz atmospheric windows with 4–8 GHz IF bandwidth are under development [6]. The Group for Advanced Receiver Development (GARD, Chalmers University of Technology) demonstrated a balanced waveguide hot-electron bolometer (HEB) mixer covering the RF band 1.25–1.39 THz and with an IF bandwidth of 3 GHz. Over the RF band the averaged DSB receiver noise temperature was better than 1200 K [7].

接收器开发，例如，对于阿塔卡马大型毫米波阵列（ALMA）[8]，刺激了单个像素超导双频带分离混频器的发展，其中波导电路元件，如分支线耦合器，被实现 [9]。波导接头复杂性导致分支线耦合器随着频率而增加。例如，典型距离在 [7] 中不超过 35 μm。因此，而不是使用，例如，铣削技术，
Figure 1. (a) This shows a balanced mixer device on the handle wafer before substrate geometry definition. Two tapered slotline waveguide antennas are connected to the 90° CPW branch-line coupler, magnified in (b) feeding two pairs of SIS junctions with one pair magnified in (c). Each twin-junction pair is connected to a separate RF blocking filter. Beam lead contacts provide ground and signal connections and hold the device suspended inside the mixer block (figure 2(a)). In (c) the alternated line transformer is indicated by a box around the region where we specify the circuit’s admittance $Y$. The section with impedance $Z_3$ is realized with an inverted microstrip transmission line whereas the sections with impedances $Z_0$ and $Z_4$ are CPW transmission lines. The microstrip line with impedance $Z_{ms}$ is the input section of the quarter-wave transformer which is part of the SIS junction tuning circuit.

photolithography together with fine copper electroplating was used to fabricate this branch-line coupler. Next-generation instruments where advanced mixer devices, such as balanced or single-sideband mixers, will be used in focal plane arrays would greatly benefit from a frequency scalable technology where key elements of these circuits (e.g. branch-line couplers or LO distribution circuits) are integrated on one chip. This would provide the possibility of producing focal plane array receivers (i.e. many pixels) in large numbers and with high yields.

In this paper we present a balanced SIS mixer on a silicon (Si) membrane. Si membrane technology and microfabrication techniques provide a possibility to overcome the difficulties of realizing balanced SIS mixers at 1 THz and above, provided that a suitable superconductor detector and transmission line technology is used. $T_{\text{rec,DSB}}$ and noise rejection have been measured within the 440–495 GHz bandwidth of our LO over an IF bandwidth of 4–8 GHz. The influence of thermal radiation superimposed with the LO signal on the mixer IF output power is measured, illustrating the mechanism of AM and thermal noise rejection. We show that $T_{\text{rec,DSB}}$ does not change when DC-biasing the balanced circuit inversely or with the same polarity if the corresponding $\Sigma$ or $\Delta$ port of the external 180° IF hybrid is used. Building on the present paper we wish to present a detailed analysis in another publication. The expected performance of the mixer chip can be determined from the quantum theory of mixing [10, 11] and results of our electromagnetic design. By comparing this analysis to the measurements we expect to determine the influence of, for example, fabrication tolerances and to identify improvements that can be implemented in future design iterations.

2. Working principle and design of the balanced SIS mixer

We start with a brief discussion of the working principle of the balanced SIS mixer device shown in figure 1(a). The circuit is realized using superconducting Nb transmission lines. Two tapered slotline antennas [12] A and B are matched via a slotline shorted stub to a $Z_0 = 43 \, \Omega$ coplanar waveguide (CPW) each connected to the input of a 90° CPW branch-line coupler with the same input impedance (magnified in figure 1(b)). At CPW discontinuities, the odd mode of the propagating TEM wave is suppressed by 3 $\mu$m wide ground connecting Nb bridges on top of a 900 nm SiO$_2$ layer that connect the ground planes at either side of the CPW. Numbers 1–4 label the coupler ports in figures 1(b) and 2(b). Signals received by antenna A (guided to port 1) and antenna B (guided to port 4) are equally distributed to ports 2 and 3 with a relative phase difference of $-\pi/2$ and $+\pi/2$, respectively. This is achieved by three branches separated by $l_b = \lambda/4$. All
branches have a length of \(l_b\) with impedances \(Z_1 = Z_0 \times 2.415\) and \(Z_2 = Z_0 \times \sqrt{2}\), cf [13]. The two output ports of the coupler with impedance \(Z_a\) are each connected to an SIS microstrip tuning circuit via an uniplanar alternate line [14] CPW-to-microstrip transformer. The uniplanar alternate line transformer section of the balanced circuit together with a circuit schematic is shown in figure 1(c). The impedance \(Z_0\) of the output ports of the branch-line coupler is matched to the input impedance \(Z_{ms}\) of 21 \(\Omega\) of the microstrip line. For \(Z_0 = Z_4\) and \(Z_{ms} = Z_3\) (i.e. with alternating impedances) the electrical length of the two transformer sections becomes

\[
\frac{1}{2\pi} \arctan \left[ \frac{Z_0/Z_{ms}}{(Z_0/Z_{ms})^2 + Z_0/Z_{ms} + 1} \right] \tag{1}
\]

For \(Z_0 = Z_{ms}\), (1) equals exactly 1/12 and for \(Z_0 \neq Z_{ms}\) it takes a smaller value.

Figure 1(c) shows one of the tuning circuits and an SIS junction pair (black dots in the inset indicate a junction). The circuit schematic explains the superconducting tuning circuit. A microstrip inductance \(L\) with length \(l_1\) compensates \(C_1\) and \(C_2\) resulting in \(Z_{in} = R_1 R_2 (R_1 + R_2)^{-1}\). The beam leads \(R_1\) and \(R_2\) being the normal state resistance of the two SIS junctions. Here \(Z_{in} = 10\ \Omega\) and \(R_1 = R_2\). A microstrip line with length \(l_2 = \lambda/4\) and input impedance \(Z_{ms}\) matches \(Z_{in}\) to the admittance \(Y\) of the RF structure. Finally, in the SIS junctions RF and LO signal are multiplied to produce the IF signal \(\nu_{IF} = |\nu_{RF} - \nu_{LO}|\). A CPW RF choke (filter) is used to block further propagation of the RF and LO signals and provides a bandpass for IF signals.

Figure 2(a) shows device A12, used for our measurements, assembled inside the mixer block. Antennas A and B with length \(l_a = 170\ \mu m\) extend into a split-block full-height waveguide cut in the \(E\) plane. The waveguide dimensions are \(b = 230\ \mu m\) and \(a = 2b\) (\(a\) is normal to the paper plane) with a step of 131 \(\mu m\) at the antenna feedpoint in the \(a\) direction and in both mixer block halves. The top face as well as the bottom face of the device is separated from the mixer block wall by a gap of 90 \(\mu m\) (figure 2(a)). The IF signal output beam leads are connected to a circuit board transmitting the IF and allowing each junction pair to be biased separately. A magnetic field, produced by an electromagnet which is attached to the mixer block, is used to suppress Cooper pair tunneling. Two corrugated horn antennas (not shown in figure 2(a)) are attached at both waveguide inputs of the mixer block to couple the free space LO and RF signal to the waveguides.

### 3. Device fabrication

The device is fabricated in-house on silicon-on-insulator (SOI) wafers with a high-resistivity (>10 k\(\Omega cm\)) device layer of 9 \(\mu m\) thickness (cf also [15]). The Nb/Al/Al\(_2\)O\(_3\)/Nb tunnel layers are deposited with DC-magnetron sputtering and patterned by UV optical lithography. The 1 \(\mu m^2\) area junction top electrodes are defined by electron-beam lithography. The 300 nm sputtered SiO\(_2\) dielectric layer is defined with standard self-aligned liftoff. A second SiO\(_2\) layer of 600 nm is added in the area of the Nb ground connection bridges loading the CPW. The final Nb wiring layer is 400 nm thick and is again defined by UV optical lithography. After defining the beam lead contacts with a sputtered gold seed layer, the beam leads are electrolytically gold-plated to a thickness of 2.5 \(\mu m\). The handle wafer bulk silicon is removed from the backside in an inductively coupled plasma deep reactive ion etch (DRIE) step stopping on the SOI buried oxide (BOX) layer. Subsequently the device substrate geometry is defined on the backside by photolithography and the individual devices are etched out with RIE to remove the BOX layer followed by an anisotropic Bosch Si etch recipe for the silicon device layer.

### 4. Experimental set-up

The mixer block is mounted in a cold optics assembly on a 4.2 K liquid helium dewar stage. The LO signal passes through a 443 \(\mu m\) thick Teflon window and the separate RF window is made of a plane slab of 505 \(\mu m\) HDPE. No special infrared coating or grooving was used on this window which has a measured transmission of 0.95 at 440 GHz, decreasing to 0.87 at 495 GHz. Infrared radiation is blocked by 200 \(\mu m\)
variable constant temperature $T_{\text{rec}}$. (b) is taken with a spectrum analyzer at the $\Sigma$ port. The IF output power averaged over $4-8$ GHz for $T_{\text{rec}}$ (figure 2(b)). Right: $T_{\text{rec,DSB}}$ is measured with IF output power averaged over $4-8$ GHz function of $V_{\text{RF}}$. The LO beamsplitter termination temperature is at constant temperature $T_{\text{bs}}$ (red dotted line) or $T_{\text{bs,c}}$ (blue dash–dotted line). The solid black curve is the mixer’s noise rejection and the dashed black line indicates $2h_{\text{vap}}/k_{B}$, with $h$ and $k_{B}$ the Planck and Boltzmann constant.

thin HDPE windows on the dewar 77 K shield. Radiation emitted by black body sources at temperatures $T_{h} = 295 K$ or $T_{c} = 77 K$ (load) is received by antenna B (figure 2(b)). The LO signal is coupled to the device by a 25 $\mu$m thin Mylar beamsplitter at 295 K. Behind the beamsplitter, thermal radiation from a load at temperatures $T_{\text{bs}}$ is superimposed with the LO signal and received by antenna A (figure 2(b)). Two cryogenic low-noise MMIC WBA13 amplifiers [16] ($T_{\text{amp}} \approx 4 K$ over $4-12$ GHz, $C$ in figure 2(b)) and two $4-10$ GHz bias-$T$ circuits are connected to the balanced mixer IF ports through the circuit board shown in figure 2(a). Both amplifiers provide a equal gain throughout all measurements in this paper. A low-noise warm amplifier (W in figure 2(b)) is used for further amplification. The combined IF output power at the output of a $180^\circ$ IF hybrid [17] (we use a rat-race coupler outside of the liquid helium dewar, figure 2(b)) is averaged over $4-8$ GHz and measured with a power meter or is measured as a function of IF frequency with a spectrum analyzer.

Thanks to the antisymmetrical $IV$ curve of an SIS junction, an additional phase shift of $\pi$ can be added to the respective IF signals by using an inverse polarity DC bias for the two SIS junction pairs. This enables the use of the $\Sigma$ port of the $180^\circ$ IF hybrid that combines the two IF signals for the balanced IF output. Noise added to the LO signal cancels at the $\Sigma$ port and is measured at the $\Delta$ port (figure 2(b)). This situation is reversed by operating the two SIS junction pairs with equal bias polarity where now $\Sigma$ is the noise port and IF signals are added at $\Delta$.

5. Noise temperature and noise rejection measurement

We determine $T_{\text{rec,DSB}}$ by measuring the ratio $Y = P_{\text{rec}}/P_{\text{rec,c}}$ using an IF output power averaged over the resolution bandwidth while a load temperature $T_{h}$ and $T_{c}$ is placed in front of the RF window (figure 2(b)). The uncorrected DSB receiver noise temperature is $T_{\text{rec,DSB}} = (T_{h} - Y T_{c})/Y$ where $T_{h}$ and $T_{c}$ are the physical temperatures of the loads (Rayleigh–Jeans limit). At 455 GHz we measured $T_{\text{rec,DSB}}$ as a function of $V_{\text{RF}}$ (resolution: 3 MHz) with one junction pair biased inversely with respect to the other pair (figure 3(a)) and with positive bias polarity for both junction pairs (figure 3(b)). In the latter case we measured no significant difference in $T_{\text{rec,DSB}}$. In figure 3(c) we show $T_{\text{rec,DSB}}$ at various LO frequencies. The IF output power was averaged over the $4-8$ GHz IF output bandwidth.

In figures 4(a) and (b) IF output power is measured as a function of $U_{\text{bias,B}}$ with constant LO beamsplitter termination temperature $T_{\text{bs,c}}$ and $T_{\text{bs,h}}$ and with constant voltage bias $U_{\text{bias,A}} = -1.55$ mV in both measurements. We denote with $U_{\text{ph}}$ voltages within the range of the first photon step below the gap of the LO pumped SIS $IV$ characteristic on the positive ($+$) and the negative ($-$) branch (figure 4(b)). The thermal power $P_{\text{bs,c}} = k_{B} T_{\text{bs,c}} B$ and $P_{\text{bs,h}} = k_{B} T_{\text{bs,h}} B$, superimposed with LO radiation and acting as noise incident on the device, is measured in the $\Delta$ branch of the IF output power trace for $U_{\text{bias,B}} = U_{\text{ph}}$. Here, $B$ is the IF bandwidth of $4-8$ GHz. Evidently for $T_{\text{bs,c}}$ less noise is added to the mixer visible in the height of the IF power trace in the $\Delta$ branch. In the $\Sigma$ branch the rejection of the noise is clearly visible, especially for the LO beamsplitter termination temperature $T_{\text{bs,h}}$. Here it is observed that the IF output power trace is shifted downwards due to the noise rejection as indicated in figure 4(b) by the region between the rectangles. This occurs for $U_{\text{bias,B}} = U_{\text{ph}}$ and in this branch we measure $T_{\text{rec,DSB}}$. SIS junction pair A provides a constant IF output power during each voltage sweep resulting in a relative shift between the blue and red traces in figures 4(a) and (b) and in an overall shift of both traces in figure 4(b) (black arrow) relative to the traces in figure 4(a).

The noise rejection of the balanced mixer is measured by the ratio $dP^{+}/dP^{-}$, $dP^{+}/dP^{-}$ being the difference in IF output power between the red and blue lines for $U_{\text{bias,B}} = +1.55$ mV.
The temperature is at constant temperature $T$.

Some of the authors of this paper recently showed that single-ended HEB devices can be reliably fabricated on 2 μm thick Si$_3$N$_4$ SOI wafers and that beamlead technology can be used to hold the devices suspended inside the mixer block even at working frequencies as high as 2.5 THz [19]. In a recent paper from the GARD School of Physics and Astronomy for financial support.

Figure 4. IF output power curves as a function of $U_{\text{bias, B}}$ ($\nu_{\text{RF}} = 455$ GHz) and the LO pumped SIS IV characteristic of the junction pair B (black solid curve). The IF output power is measured at the $\Sigma$ port as a function of $U_{\text{bias, B}}$ (figure 2(b)). In (a) the LO beamsplitter termination temperature is at constant temperature $T_{\text{bs,c}}$ and in (b) at $T_{\text{bs,h}}$. The red (blue) curve was taken with a 295 K (77 K) load in front of the RF port. For $U_{\text{bias, B}} < 0$, $T_{\text{rec, DSB}}$ is measured at the $\Sigma$ port. The dashed vertical line separates the $\Delta$ from the $\Sigma$ branch of the IF output power trace. In (b) the IF output power trace is shifted up with respect to the trace shown in (a) due to the excess of thermal noise incident at the LO port.

Matching pairs of devices. A planar coupler in normal metal technology, because of the high frequency, is fabricated with integrated mixer devices, but offers no possibility to counteract fabrication tolerances after device processing.

7. Conclusion

To conclude, we have measured the uncorrected DSB receiver noise temperature of our device between 440 and 495 GHz and obtain values ranging from 70 to 130 K representing state-of-the-art performance. An inverse polarity bias for the two mixers does not change the performance of the device compared to an equal bias polarity for the two mixers, provided the sum and the difference port of the IF hybrid is used, respectively. The noise rejection of the device is between 6 and 18 dB. Noise added to the mixer’s LO port can be directly measured in the IF output power and does not significantly increase $T_{\text{rec, DSB}}$. The noise rejection mechanism is directly observable in the IF output power as a function of the bias voltage over the whole voltage range of the photon step.

Acknowledgments

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