A 385-500GHz Balanced Mixer with a Waveguide Quadrature Hybrid Coupler

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***Abstract*—We developed a 385-500GHz balanced mixer with a waveguide quadrature hybrid coupler. The balanced mixer consists of an RF quadrature hybrid coupler, two double sideband (DSB) SIS mixers with noise temperature of ~ 60K, and an IF 180 degree hybrid coupler covering 4 - 8 GHz IF band. An RF quadrature hybrid coupler was designed and fabricated whose fabrication error was within 5μm. The noise temperatures of the balanced mixer was similar to those of two DSB mixers in spite of adding an RF quadrature hybrid and an IF coupler. The required LO power for pumping the balanced mixer was reduced by ~12dB on average compared with those for the DSB mixers and -15dB coupler. The sideband noise of the local oscillator (a quintupler + a Gunn oscillator) was measured to be 20K at offset frequency of 4 – 8 GHz, which corresponds to 70K/μW. To authors' knowledge, this is the first direct measurement of LO sideband noise at submillimeter range. If a varistor quintupler degrades the signal-to-noise by 10dB (K. Saini 2003 [1]), the sideband noise of a Gunn oscillator is 7K/μW at the offset frequency of 0.8-1.6 GHz.**

***Index Terms*—balanced mixer, LO sideband noise, noise temperature**

I. INTRODUCTION

BALANCED mixers are useful components of receivers for radio astronomy at submillimeter and teraherz frequency range, where enough LO power is not available. Balanced mixers have some advantages over single-ended mixers. 1: The required LO power is substantially less than that of a single-ended mixer. 2: The LO sideband noise can be reduced. So far, several balanced mixers have been developed at submillimeter-wave bands, such as a 180-420GHz waveguide type [2], a 200-300GHz coplanar waveguide type [3], and a 530GHz quasioptical type [4], and a 1.32THz waveguide type (HEB) [5]. However, noise temperature of a balanced mixer and a single-ended mixer has not been compared. In present work, we not only compare noise temperature of a balanced mixer and a single-ended mixer, but also derive sideband noise of a local oscillator.

There are two types of balanced mixers. One is quadrature-hybrid type, and the other is 180-degree-hybrid type. In present work, we used the former type of the balanced mixer, because the quadrature hybrid at this frequency has been established by M. Kamikura et al. [6].

LO signal is usually coupled into a single-ended mixer with a LO coupler. The coupling of LO signal is ~ -15 to -20 dB, so that most of LO power is wasted in LO coupler. Taking account of use of 3-dB coupler in balanced mixers, the required LO power for a balanced mixer can be reduced by 12-17dB compared with that for single-ended mixers.

II. BALANCED MIXER AND SETUP

A. RF quadrature hybrid

We designed and fabricated a waveguide type quadrature hybrid coupler optimized to 385-500 GHz frequency band [7]. The waveguide size is 508μm × 254μm (WR2.0). The design values and measurement values of the branch lines are shown in Fig.1. The fabrication error is within ~ 5μm.

We designed it with a commercial 3D electromagnetic field simulator, HFSS (High Frequency Structure Simulator). The quadrature hybrid is split at the edge of the E-plane to reduce the loss resulting from the misalignment of the two split blocks [6]. The transmission of this coupler was measured and was similar to that of [6].

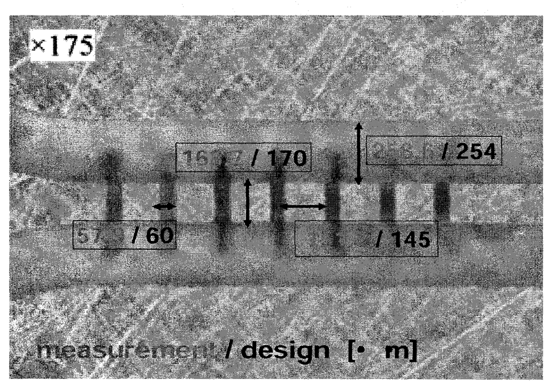

Fig. 1. The macrograph of blanch lines of a 90 degree hybrid coupler. Dimensions are in μm. The fabrication error is within ~ 5μm. The depth of the waveguide is 508 μm.

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B. Single-ended mixer

Single ended mixer for this balanced mixer is an SIS mixer developed by W. L. Shan et al. [8] [9]. It is Nb-based parallel connected twin junction. The Josephson current was suppressed with a super-conducting magnet. The input waveguide size is WR2.0 (508 × 254 μm).

C. Local oscillator

Local oscillator is composed of a Gunn oscillator (~ 90 GHz) from RPG [10] and a cryogenic frequency multiplier or a varistor quintupler from VDI [11]. The LO power was measured at the input of the balanced mixer at room temperature. If the quintupler is cooled from 300K to 12K, its efficiency would increase by 20%.

D. The balanced mixer

Fig.2 shows the block diagram of the balanced mixer and its system. The balanced mixer consists of an RF quadrature hybrid coupler, two single-ended (DSB) mixers, and an IF 180 degree hybrid coupler. In the IF system, isolators and IF amplifiers are used in and out of the cryostat.

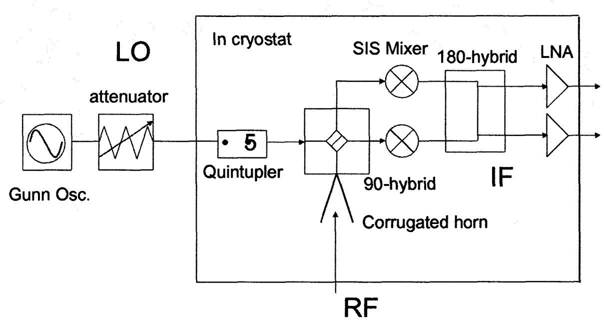

Fig. 2. Block diagram of the balanced mixer. We used an RF quadrature-type balanced mixer. The balanced mixer consists of an RF quadrature hybrid, two SIS mixers, and an IF 180 degree hybrid.

III. MEASUREMENTS

A. Noise temperature

We first measured the noise temperatures of two single-ended mixers by Y-factor method using hot (300K) and cold (77K) load. The mixers were in a vacuum dewar cooled to about 4 K. The RF signal was fed into the LO coupler via a corrugated horn [12]. Noise temperatures of the single-ended SIS mixers were measured with a -15 dB waveguide LO coupler [6]. Then the noise temperature of the balanced mixer was measured.

Fig.3 and Fig.4 show the I-V curves and noise temperatures of the single-ended mixers and the balanced mixer respectively. At LO frequency of 450GHz, the balanced mixer has almost the same noise temperature as the single-ended mixers.

Frequency dependence of noise temperatures of single-ended mixers and the balanced mixer is shown in Fig.5. The noise temperatures of two single-ended mixers are similar (especially at higher frequencies), so that the conversion gain of single-ended mixers may be similar at higher frequencies. As expected, there is no significant increase in noise temperature of the balanced mixer in spite of adding the quadrature hybrid and the IF 180 degree hybrid.

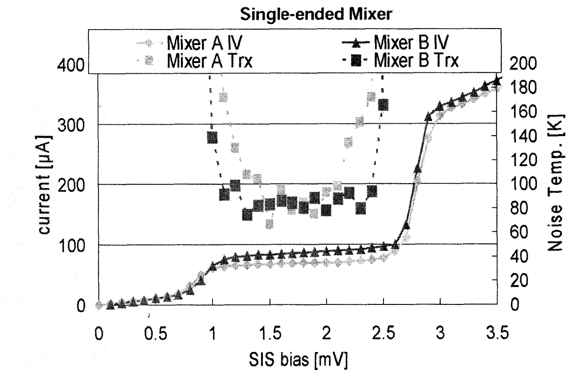

Fig.3. The IV curves and noise temperatures of the single-ended mixers in the IF band of 4-8GHz. The LO frequency is 450GHz.

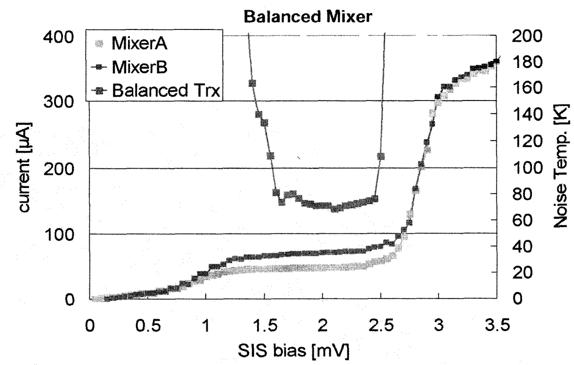

Fig. 4. The IV curves and noise temperatures of the balanced mixer in the IF band of 4-8GHz. The LO frequency is 450GHz (band center).

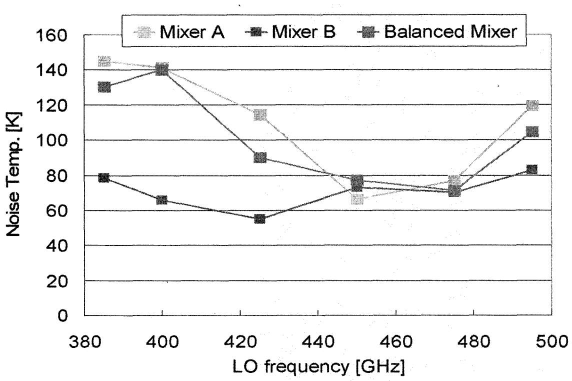

Fig. 5. The noise temperature of two single-ended mixers and the balanced mixer. There is no significant increase of noise temperature due to adding the RF quadrature hybrid and IF 180 degree hybrid.

B. LO power

Fig.6 shows the required LO powers for two single-ended mixers and the balanced mixer.•• In case of measuring noise temperature of the single-ended mixers and the balanced mixer at 4K, the parameters of the Gunn oscillator and the attenuator were recorded. The LO powers required for the single-ended mixers and the balanced mixer were measured at room temperature with the same parameters as in case of 4K. Then we compared the measured LO power of the balanced mixer with that of each single-ended mixer. The result is shown in Fig.6. The cooling effect of 20 % increase in efficiency of a quintupler is common to both the single-ended mixers and the balanced mixer. The effect is not

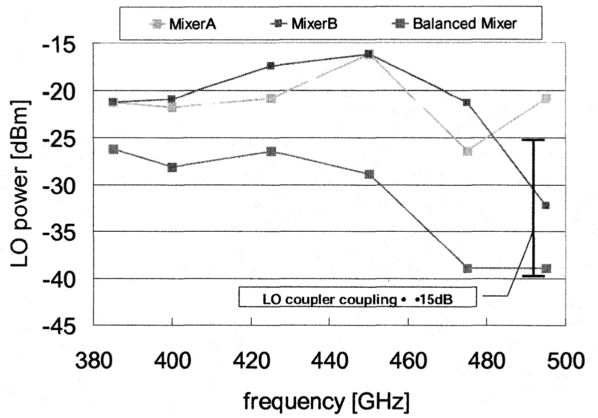

Fig. 6. Required LO power required for pumping SIS mixers was measured at the input of the balanced mixer at room temperature. The required LO power is reduced by ~12dB on average. The LO coupling of -15 dB for single-ended mixers is indicated for reference.

corrected in this Figure.

It can be found that the required LO power for the balanced mixer is reduced by ~ 12dB on average. Furthermore, at higher frequencies the LO power reduction is better than at lower frequencies. This is consistent with a fact that the two DSB mixers have the same noise temperature (see Fig.5). According to Fig.5, at lower frequencies two SIS mixers may have relatively different conversion losses, but at higher frequencies they may have similar conversion losses.

C. LO sideband noise

We measured LO sideband noise of a quintupler + a Gunn oscillator. Fig.7 explains a derivation of LO sideband noise. The leakage δ which expresses the ratio of the LO sideband noise outputted from the signal port is defined (see Fig.7).

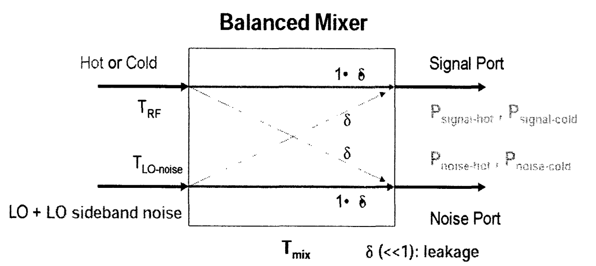

Fig. 7. Simplified derivation of LO sideband noise from a balanced mixer. The balanced mixer consisting of a quadrature hybrid, two single-ended SIS mixers, and an 180 degree hybrid can be regarded as one component whose noise temperature is T_{mix}. The leakage δ is 0 if the balanced mixer works ideally.

If the balanced mixer works ideal, the δ should be 0. In fact, the leakage of the LO sideband noise and that of the signal are not the same, but we considered those are the same in the first order approximation. P_{signal} and P_{noise} are the powers outputted from the signal and noise ports, respectively. Then, the following equations are derived. (Δf: band width)

$$P_{signal} = G_{IFsignal} k_B \left[(1-\delta)T_{RF} + \{T_{mix} + \delta T_{LO\text{-}noise}\}\right]\Delta f \quad (1)$$

$$P_{noise} = G_{IFnoise} k_B \left[\delta T_{RF} + \{T_{mix} + (1-\delta) T_{LO\text{-}noise}\}\right]\Delta f \quad (2)$$

Fig.8-10 shows the results derived from measurements with integrated IF frequency of 4 – 8 GHz. The signal and noise ports interchange with changing SIS bias polarity. The four data points from bias polarities of two SIS mixers were obtained.

The values of δ are lower at higher frequencies, which is consistent with the similar conversion gains of two SIS mixers at higher frequencies. The value of 0.03 corresponds to noise reduction ratio of – 17 dB. Fig.9 shows the values of T_{mix}. The result is consistent with the measured noise temperatures of the balanced mixer (Fig.5). Fig.10 shows the LO sideband noise ($T_{LO\text{-}noise}$) integrated in the IF frequency of 4 – 8 GHz.

Fig.11 shows IF-frequency dependence of δ, T_{mix}, and $T_{LO\text{-}noise}$. The mixer noise temperature T_{mix} and the leakage δ are flat over IF frequency from 4 – 8 GHz, but the LO sideband noise $T_{LO\text{-}noise}$ has large ripples. It is due to standing

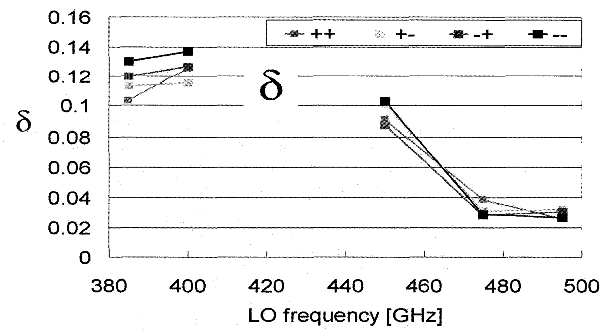

Fig. 8. The measurement result of the leakage δ.
The difference of the colors expresses the polarity of two mixer biases.

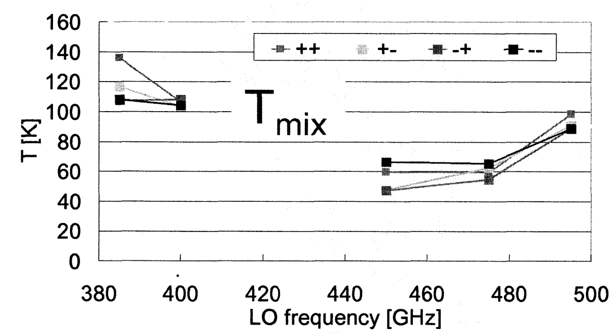

Fig. 9. Derived noise temperature of the balanced mixer in the IF frequency of 4 – 8 GHz. The difference of color expresses the polarity of two mixer

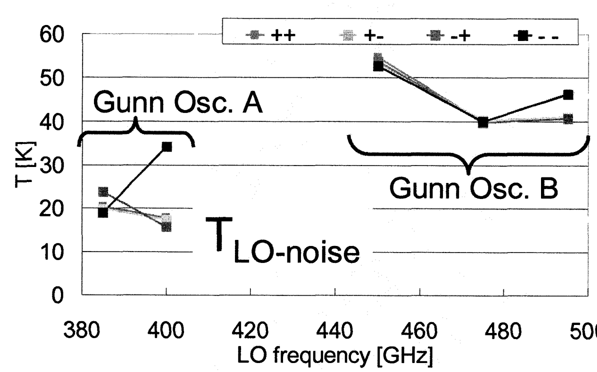

Fig. 10. Derived LO sideband noise ($T_{LO\text{-}noise}$) in the IF frequency of 4-8 GHz Note that a Gunn oscillator used for 380–400GHz is different from that for 450–500 GHz. The difference of color expresses the polarity of two mixer biases.

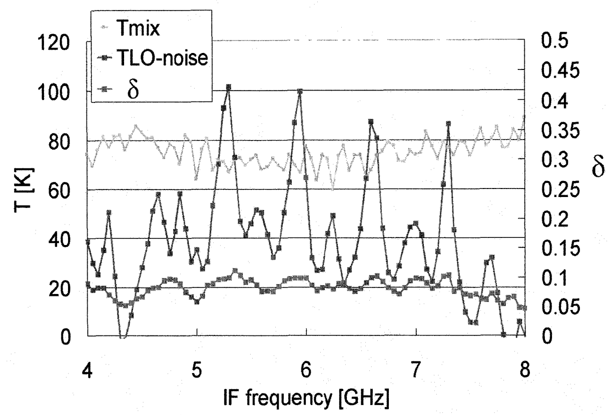

Fig. 11. IF-frequency dependence of leakage δ, mixer noise temperature T_{mix}, and LO sideband noise $T_{LO\text{-}noise}$.

waves in the LO path. The LO sideband noise without the ripple was ~ 20K. $T_{LO\text{-}noise}$ at lower frequencies where there wouldn't be such large ripples was also ~ 20K. This means that noise temperature of a DSB mixer at this frequency includes LO sideband noise of 10K. This fact is consistent with the difference of noise temperatures of Fig.5 and Fig.9.

Based on the calculated LO power for a SIS junction of 0.13μW [13], the input power for the balanced mixer is ~ 0.3μW (3dB quadrature hybrid). So, the LO sideband noise whose offset is 4-8GHz is 70K/μW (quintupler + Gunn oscillator). K. Saini (2003) [1] calculated that a varistor quintupler degrades the signal-to-noise by 10dB. According to it, the sideband noise of a Gunn oscillator corresponds to ~ 7K/μW whose offset is 0.8-1.6GHz.

The shot noise is given as the following equation [14].

$$T_{shot} = \frac{P_{shot}}{k_B \Delta f} = \frac{2e}{k_B} I_{bias} R \quad (3)$$

Substituting I_{bias}=0.2A and R=10V/0.2A=50Ω (operating values of the Gunn oscillator) into the above equation yields $T_{shot}=2.3\times10^5$ K. The output power of the carrier signal of a Gunn oscillator is $\sim 3\times10^4$ μW. Therefore, the sideband noise of Gunn oscillator is estimated to ~ 8K/μW or -160 dBc/Hz from shot noise.

Following the above results, LO sideband noise for an typical SIS mixer covering any frequencies can be estimated. The LO power for a single-ended mixer at 100GHz is ([13])

$$P_{LO} = \left(\alpha_n \frac{N_j hf}{e}\right)^2 \Big/ 2R_N \;=\; 0.017\,[\mu W] \quad (4)$$

,where α_n ~ 1, N_j (the number of the junction)=2, h: Planck constant, f=100GHz, e: electron charge magnitude, and R_N (normal resistance)=20Ω. Thus, a single-ended SIS mixer pumped with a Gunn oscillator at 100GHz should have an LO sideband noise of ~ 7 [K/μW] × 0.017 [μW] = 0.12 [K], which is not easy to measure. The LO power required for pumping an SIS mixer is proportional to the square of frequency [13]. In general, a multiplier degrades sideband noise by 20log(n) or the square of multiplication (n: multiplication) [14]. That is, the LO sideband noise of multiplier chain for SIS mixers is roughly proportional to the 4th power of frequency. For example, a single-ended SIS mixer operating at 1THz with 10 times multiplication would have a sideband noise of 10 [K]×(1THz / 500GHz)^4 = 160 [K] ~ 3.3hf/k, which can be major of the low noise THz receiver.

IV. Conclusion

We developed and measured a 385-500GHz waveguide and modular type balanced mixer with a waveguide quadrature hybrid coupler. The measured noise temperature is almost the same as that of each single-ended mixer. There is no significant increase of noise temperature due to adding the quadrature hybrid and the IF 180 degree hybrid. The required LO power is less than the single ended mixers by ~ 12 dB on average. Furthermore, based on the result of measurement of the output power we estimated the LO sideband noise using the balanced mixer. LO sideband noise (a quintupler + a Gunn oscillator) for two mixers was measured to be ~ 20K or 70K/μW. Sideband noise of a Gunn oscillator was derived to be ~ 7K/μW, which is consistent with shot noise.

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