Performance of a Sideband Separating SIS Mixer for 85-115 GHz

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ABSTRACT

We present results of the development and measurements of a heterodyne sideband separating SIS mixer for 85-115 GHz band. The sideband separation is achieved by using a quadrature scheme where a local oscillator (LO) pumps two identical mixer junctions with 90° phase difference. A key component in the mixer is a waveguide to microstrip double probe transition used as a power divider to split the input RF signal and to provide transition from waveguide to microstrip line. The double probe transition enables the integration of all mixer components on a single compact substrate. The design also involves coupled lines directional couplers to introduce the LO power to the mixer junctions. An additional pair of SIS junctions is used to provide termination loads for the idle ports of the couplers. Several mixer chips were tested and similar and consistent performance was obtained. The best single sideband noise temperature is below 40 K with IF bandwidth 3.4-4.6 GHz. The sideband suppression ratio is better than 12 dB for both sidebands across the entire RF band. The mixer was also successfully tested with 4-8 GHz IF band. In this paper we present complete mixer characterization data.
Keywords: SIS mixer, sideband separating receiver, waveguide-to-microstrip transition, double probe transition, sideband suppression ratio

1. INTRODUCTION

The advance of two big international projects ALMA and APEX prompted the development of sideband separating (2SB) mixer technology for mm-wavelengths [1]-[5]. The motivation for using 2SB mixers for radio astronomical applications at mm-wavelengths is that the noise performance of a double-side band (DSB) heterodyne receiver is often limited by the atmospheric noise fed into the system via the image band. Thus, to further increase the system sensitivity, 2SB or single sideband (SSB) operation is preferred where the image band is either dissipated on a low temperature load or is terminated reactively.

2SB mixers are based on a quadrature scheme where the RF and LO signals are divided and introduced to two identical DSB mixers. The IF components of both DSB mixers are combined in an IF hybrid where the sideband cancellation takes place. The quadrature scheme requires 90^0 phase delay for either RF or LO signals in one of the mixer channels.

One kind of 2SB mixers is the one using a branch-line coupler at the mixer input, which divides the RF signal with the required 90^0 phase delay (LO is applied in phase). The branch-line coupler is a 4 port device where the fourth port is terminated by a low-temperature load. This load is also a source of RF thermal noise, which is down-converted and present at the IF output ports. This kind of 2SB mixers are equivalent to two SSB mixers where the RF-image port is terminated/dissipated in a low-temperature load.

An alternative way to build a 2SB mixer is to use a three-port structure, which does not require any resistive termination and divides the RF signal with 0 or 180^0 phase difference. In this case, the required 90^0 phase delay is introduced in the LO channel by using, for example, a branch-line coupler. This alternative is illustrated in Figure 1 and is equivalent to two SSB mixers where the image port is reactively terminated [6].

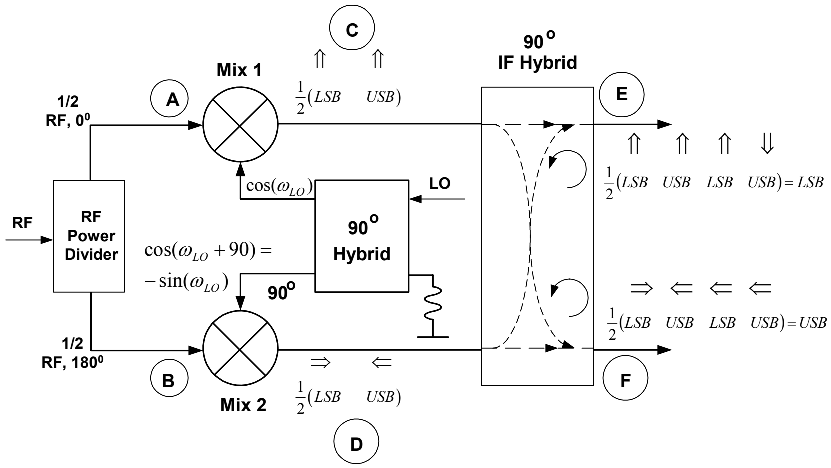

Figure 1 Block diagram of the 2SB mixer. Sideband separation is achieved by using a quadrature scheme where two identical mixer junctions are pumped by a local oscillator (LO) with 90° phase difference. To illustrate the sideband cancellation, the relative phases of the sideband signals are shown at different points of the mixer. USB and LSB stand for Upper and Lower Side Band respectively. The RF power divider is a 3-port structure, which does not contain resistive terminations.

2. MIXER DESIGN

The mixer block layout, shown in Figure 2, consists of two identical parts dividing symmetrically all waveguide structures (split-block technique). The RF input is a corrugated horn divided into two sections to facilitate the machining. A waveguide 3dB hybrid is used to divide the LO power and to introduce the required 90^0 phase delay. The bottom part of the mixer block accommodates the mixer substrate, bias-T filters to introduce DC bias for the junctions, and an absorber to terminate the idle port of the LO 90^0 hybrid. The LO power is then coupled to the ends of the substrate through waveguide to microstrip transitions.

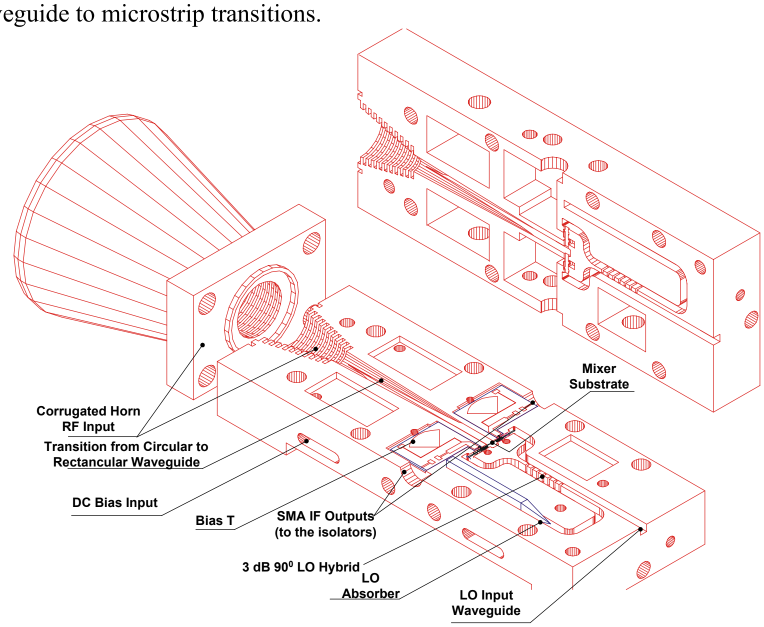

Figure 2 Layout of the sideband separating mixer. The mixer block consists of two identical parts dividing symmetrically all waveguide structures. Waveguide cross-section is 1.2 / 2.4 mm.

A closer look at the mixer substrate is presented in Figure 3. To ensure a high degree of symmetry in the SIS junction performance, most of the mixer components are integrated on the same compact substrate.

To divide the input RF signal and to couple it to the substrate we designed a special structure, a waveguide to microstrip double probe transition. This structure has a simple geometry and does not require any lumped termination load. Since the E field oscillates in parallel to the probes, the waveguide to microstrip double probe transition is naturally a 180^0 phase shifter introducing a constant phase difference for the divided RF signals. It also gives very good magnitude symmetry of the divided RF signal over the whole waveguide dominant mode, which is a critical requirement for obtaining a good degree of sideband separation. The measured magnitude and phase imbalance introduced by the waveguide to microstrip double probe transition is 0.3 dB and 0^0 in the band 85-115 GHz [7].

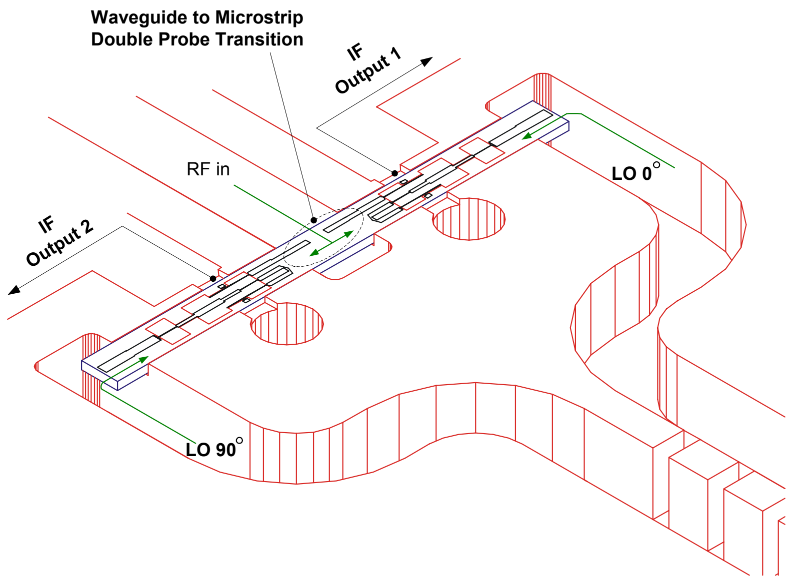

Figure 3 The mixer substrate penetrates 3 waveguides in the mixer block. The divided LO power is introduced at the ends of the substrate while the RF power is coupled to the substrate in the middle and divided between the two mixer junctions by the waveguide to microstrip double probe transition. The mixer substrate is a Z cut crystal quartz with dimensions 0.7 / 8.74 / 0.15mm (W/L/H). The substrate size is chosen such that it does not allow waveguide modes inside the substrate channel.

Figure 5 shows an enlarged section of the mixer substrate. The divided LO power is coupled at the end of the substrate via a waveguide to microstrip transition and transmitted to a 15 dB LO-directional coupler through a microstrip circuit. The RF and LO signals are then fed to each of the mixer junctions with its tuning circuitry. The rest of the LO power at the idle port of the coupler is terminated by a second SIS junction with its tuning circuitry. This SIS-termination absorbs 15 dB more LO power than the mixer junction and becomes over-pumped, its non-linear current-voltage (I-V) curve straightens and thus behaves as a lumped resistor (see Figure 6).

The degree of sideband suppression is directly related to the magnitude and phase balance of the RF and LO power applied to the mixers and the symmetry of the circuitry. Therefore it is important to provide reflection-free terminations for the LO directional coupler because a part of a reflected LO signal from one branch of the mixer will be directed through the waveguide to microstrip double probe transition to the other and thus degrade the sideband separation. For that reason, we keep the possibility to independently bias the load junctions and thus compensate a possible minor impedance mismatch caused by, for example, a spread of the nominal value of junction's normal state resistance. Figure 4 shows the calculated complex large-signal impedance of the SIS-load junction when pumped with α=5.6, which corresponds to 15 dB higher power than the one required for optimum mixer performance (α=1), α is the normalized LO amplitude $\alpha = \frac{V_{LO}}{\hbar\omega / e}$.

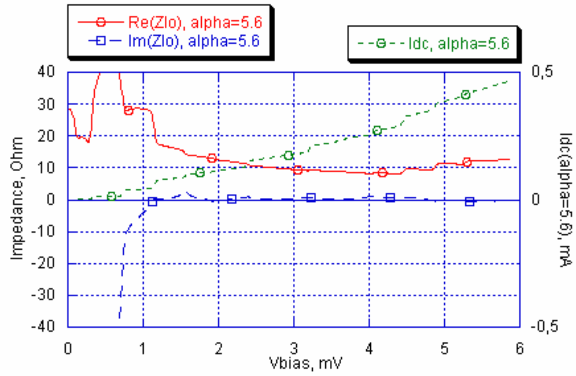

Figure 4 The complex large-signal impedance vs. bias voltage of the SIS-load junction pumped with LO power 15 dB higher than the optimum mixer-junction power (α=5.6 at every bias point). The figure shows also the straighten I_{dc}.

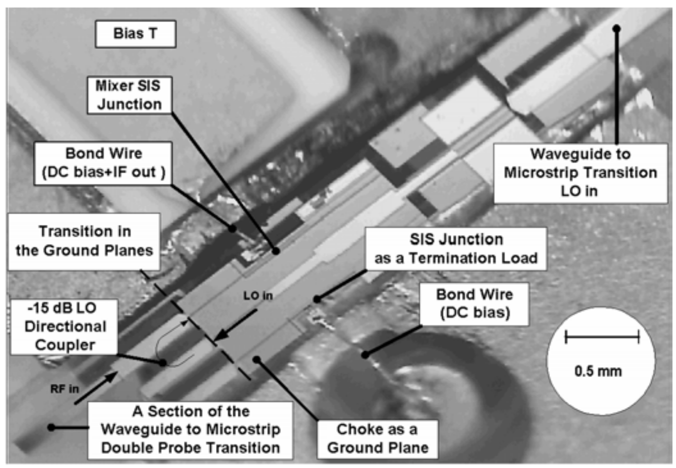

Figure 5 A closer view of the mixer components. In order to minimize the loss of RF power, the LO is injected to the RF line through a -15dB directional coupler. A second SIS junction and its tuning circuitry provides real impedance to terminate the rest of the LO at the idle port of the LO coupler. To avoid critically small spacing between the lines, the LO coupler uses the 0.15 mm thick crystal quartz substrate as a dielectric and substrate backside metallization as a ground plane. The choke serves as a ground plane for the rest of the circuitry.

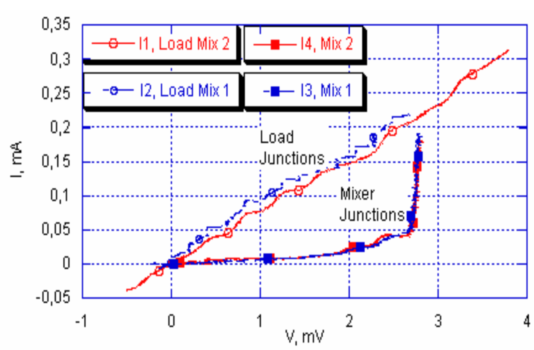

Figure 6 Junctions' I-V curves in the presence of LO power. The mixer junctions are pumped with optimum power for best sensitivity, while load junctions are over pumped being exposed to 15 dB higher power. The pairs of I-V curves show excellent symmetry giving good prospects for high degree of sideband separation.

3. MEASUREMENTS

A full characterization of a 2SB mixer requires measurement of its equivalent noise temperature and sideband suppression ratios. The equivalent noise temperature can be presented in terms of DSB or SSB temperatures. In contrast to an ideal DSB mixer, a 2SB mixer equivalent noise temperature T_{SSB} can not be measured without knowing sideband suppression ratios (the sidebands gain). In order to calculate the T_{SSB} of a 2SB mixer we use the T_{DSB} noise temperature derived from Y-factor measurements of the 2SB mixer, and the measured sideband suppression ratios.

3.1. Measuring the DSB noise temperature of a 2SB mixer

In terms of equivalent noise temperature we can consider a 2SB mixer as a 4-port black box [8] characterized by its conversion gains as shown in Figure 7.

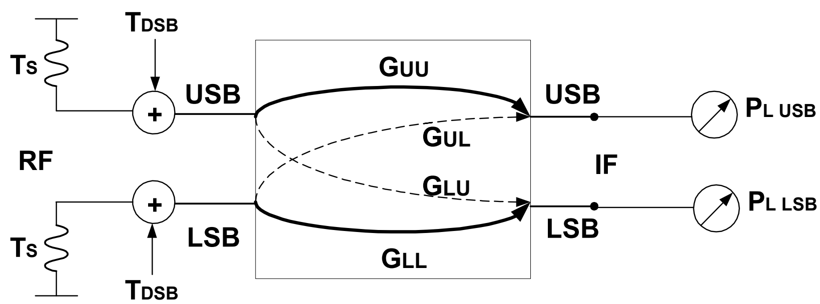

Figure 7 The sideband separating mixer characterized by its DSB equivalent noise temperature. T_{DSB} is distributed between both sidebands as in the case of a DSB mixer. T_S accounts for the temperature of the sideband source terminations, in a practical measurement both inputs would have the same temperature. G_{UU} and G_{LL} are gain coefficients describing conversion efficiency for RF-USB to IF-USB and RF-LSB to IF-LSB. G_{UL} and G_{LU} are similar coefficients reflecting the separation non-ideality of the mixer.

We can write the power at the USB IF output as:

$$P_{L\,USB} = kB\left[(T_S + T_{DSB})G_{UU} + (T_S + T_{DSB})G_{UL}\right].$$

Placing hot and cold loads for T_S and measuring the ratio of $Y = P_{L\,HOT}/P_{L\,COLD}$ gives:

$$Y = \frac{(T_{HOT} + T_{DSB})G_{UU} + (T_{HOT} + T_{DSB})G_{UL}}{(T_{COLD} + T_{DSB})G_{UU} + (T_{COLD} + T_{DSB})G_{UL}} = \frac{T_{HOT}\left(1 + \frac{G_{UL}}{G_{UU}}\right) + T_{DSB}\left(1 + \frac{G_{UL}}{G_{UU}}\right)}{T_{COLD}\left(1 + \frac{G_{UL}}{G_{UU}}\right) + T_{DSB}\left(1 + \frac{G_{UL}}{G_{UU}}\right)} = \frac{T_{HOT} + T_{DSB}}{T_{COLD} + T_{DSB}}.$$

Finally, we arrive to the result:

$$T_{DSB} = \frac{T_{HOT} - YT_{COLD}}{Y - 1}.$$

3.2. Measuring the SSB noise temperature of a 2SB mixer

In the same way as in Figure 7 we can represent the 2SB as a black box with mixer noise contribution assigned to only one of the sidebands.

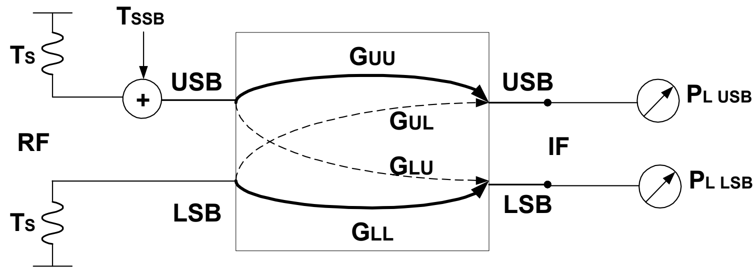

Figure 8 The sideband separating mixer characterized by its SSB equivalent noise temperature. The mixer noise temperature T_{SSB} is contributed to only one of the sidebands.

In the same way as for T_{DSB} the measured Y factor can be written:

$$Y = \frac{(T_{HOT} + T_{SSB})G_{UU} + T_{HOT}G_{UL}}{(T_{COLD} + T_{SSB})G_{UU} + T_{COLD}G_{UL}} = \frac{T_{SSB} + T_{HOT}\left(1 + \frac{G_{UL}}{G_{UU}}\right)}{T_{SSB} + T_{COLD}\left(1 + \frac{G_{UL}}{G_{UU}}\right)}.$$

Finally:

$$T_{SSB} = \left(1 + \frac{G_{UL}}{G_{UU}}\right)\frac{T_{HOT} - YT_{COLD}}{Y - 1} = \left(1 + \frac{G_{UL}}{G_{UU}}\right)T_{DSB}. \qquad (3.1)$$

The same can be applied for T_{SSB} in the other sideband, for an ideal sideband separating mixer:

$$T_{SSB} = T_{DSB} = \frac{T_{HOT} - YT_{COLD}}{Y - 1}$$

From (3.1) it is seen that for a practical mixer where the sideband separation is not perfect, calculation of T_{SSB} requires knowledge of the sideband rejection ratios $R_U=G_{UU}/G_{UL}$ regarding the USB and $R_L=G_{LL}/G_{LU}$ for the lower sideband.

3.3. Measuring the sideband suppression ratio

One way of measuring the sideband suppression ratios is to measure the mixer response to a continuous wave (CW) source placed at either the lower or upper sidebands. For example, a CW signal placed at the LSB ($f_{CW}=f_{LO}-f_{IF}$) of an ideal 2SB mixer should only be seen at the LSB IF output with no response at the USB port. Similarly, placing the CW at the USB should produce a peak at IF in the USB and give no response in the LSB output. This technique is illustrated in Figure 9.

Since real mm-wave mixers are not ideal, the CW signal is seen at both IF outputs. In this case, measuring the sideband suppression ratios R_U, R_L results in measuring the difference in the observed peak value referred to the noise level at the corresponding output.

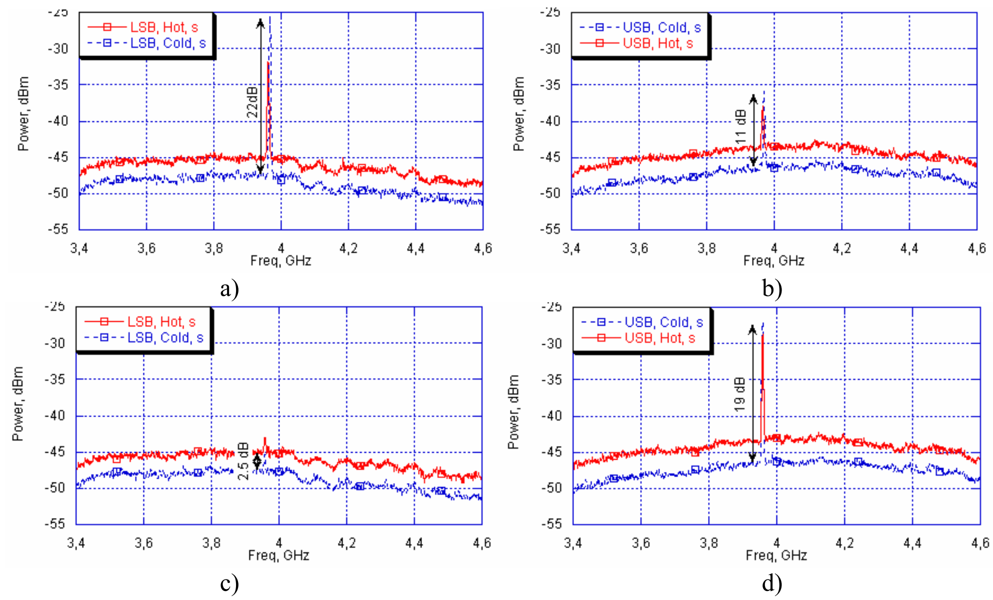

Figure 9 An example of measuring the sideband separation ratios. A CW signal is transmitted in the LSB a) and b) and the spectrum is taken for both LSB a) and USB b) IF outputs. The size of the CW peak at IF is determined and thus the ratio of USB suppression is: R_L*=22dB-11dB=11dB*. In the same way for the LSB suppression ratio a CW signal is generated in the USB c) and d). The ratio of LSB suppression is R_U*=19dB-2.5dB=16.5dB*. The sideband suppression measurements are given for two mixer input terminations: hot load - solid lines and cold load dotted lines.

3.4. Results with IF bandwidth 3.4-4.6 GHz

The 2SB mixer was measured in two configurations with IF 3.4-4.6 GHz and IF hybrid following the amplifiers, and with IF 4-8 GHz and amplifiers following the IF hybrid. The results from the measurements of SSB equivalent noise temperature and sideband suppression ratios are presented in Figure 10, 12.

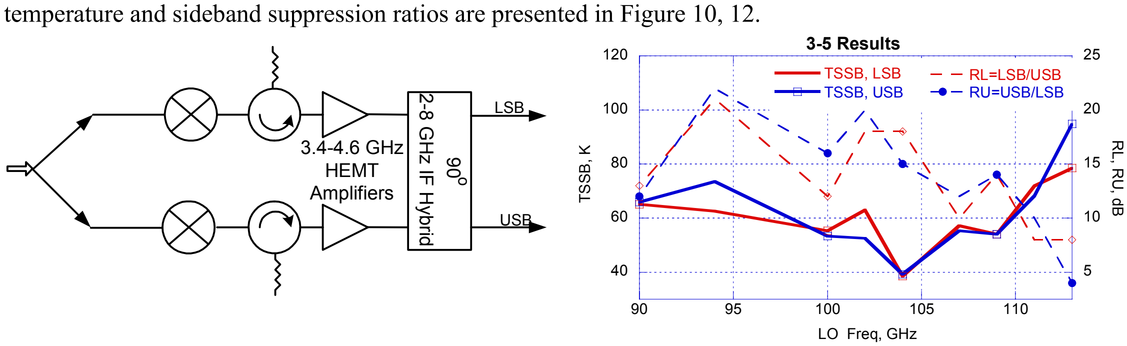

Figure 10 Measured SSB equivalent noise temperature T_{SSB} – solid lines, and sideband suppression ratios R_U, R_L-dashed lines vs. LO frequency, (equivalent to RF band of 86-118GHz with 4 GHz IF center frequency). IF band is 3.4-4.6 GHz and the IF hybrid follows the amplifiers.

In order to check the consistency in the measured sideband suppression ratios, R_U, R_L are calculated and compared for a number of CW frequencies in the USB/LSB. Figure 11 shows an example of the variation of R_U, R_L vs. IF frequency for a fixed LO frequency and mixer configuration from Figure 10. We believe that the observed variation can be contributed mostly to the asymmetry produced by the IF hybrid and cold amplifiers.

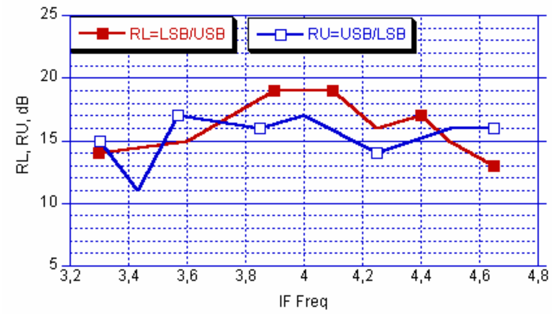

Figure 11 An example of sideband separation ratios as a function of the IF frequency. The plot is obtained for a single LO frequency and by sweeping the CW source along the RF sidebands in the case of IF 3.4-4.6 GHz.

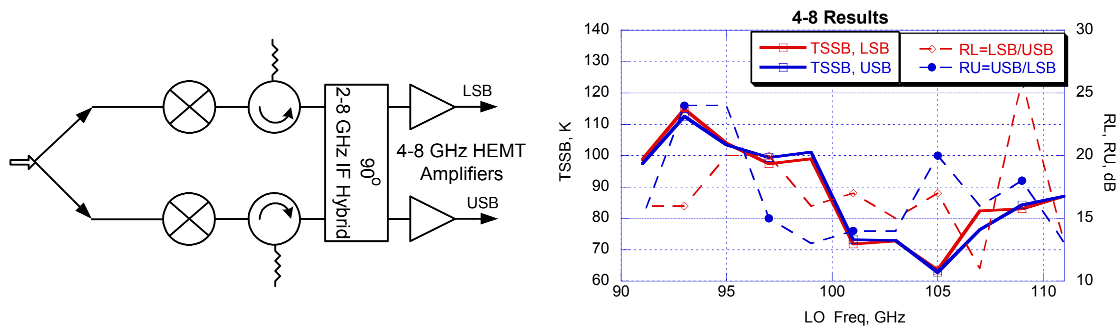

Figure 12 Measured SSB equivalent noise temperature T_{SSB} – solid lines, and sideband suppression ratios R_U, R_L-dashed lines vs. LO frequency, (equivalent to RF band of 85-117GHz with 6 GHz IF center frequency). IF band is 4-8 GHz and the IF hybrid is in front of the amplifiers.

4. CONCLUSION

Several mixer chips were tested and similar and consistent performance was obtained. The best single sideband noise temperature with IF 3.4 - 4.6 GHz (configuration 1 in Figure 10) is below 40 K with a sideband suppression ratio above 12 dB for both sidebands over the RF band. The noise contribution of the IF chain was measured to be 6 K.

Configuration 2 (Figure 12) gives about 20 K higher SSB noise temperature but also a better sideband suppression. This extra noise is partly associated with the fact that 4-8 GHz amplifiers are slightly noisier than 3.4-4.6 GHz ones, partly because the IF hybrid, placed in front of the amplifiers, introduces extra loss. However we believe that it is this configuration that should be used for practical 2SB mixers (especially with 4-8 GHz IF band) since tuning the mixer for optimum noise/sideband suppression is to a large extent simplified compared to configuration 1, which requires very well balanced IF amplifiers. The measured IF noise contribution for this configuration is about 10 K.

The measured noise temperatures include losses in all passive components in front of the mixer: a 290 K vacuum window of the cryostat, a 77 K IR filter and a lens at 4 K, all made of PTFE.

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