Design and Characterization of a Sideband Separating SIS Mixer for 85-115 GHz

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Abstract

This work presents 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 over a 4-8 GHz IF band.

Introduction

Any mixer receiving narrow band signals provides a higher signal-to-noise ratio if the image channel is terminated in a low temperature termination. The motivation for using sideband separating (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.

Sideband separating Mixers

A 2SB mixer performance can be achieved using 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 does not use any tunable RF filters but requires 90^0 phase delay for either RF or LO signals in one of the mixer channels. Designs where the RF signal is applied with 90^0 delay and the LO in-phase is illustrated in the figure below and has been demonstrated for mm-wavelengths [1]-[4]. The RF power divider is normally a 4 port device - a branch-line coupler [1]-[4] or a magic-T [5]. The fourth port of the RF power divider is terminated in a low-temperature load that is also a source of RF thermal noise which is down-converted and present at the IF output ports.

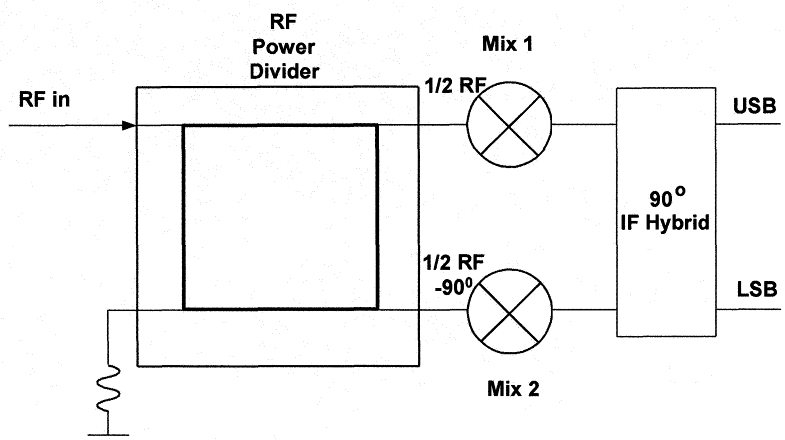

Figure 1 Block-diagram of the 2SB mixer demonstrated in [1]-[4]. The RF signal is divided and delayed by using a branch line coupler at the input, the LO power is applied in-phase to both mixers.

In the mixer design presented here we use an alternative way to achieve a 2SB operation. Instead of a RF branch-line coupler, we use a three-port structure, a waveguide to microstrip double probe transition, which divides the RF signal with a constant 180^0 phase difference [6], [7] and does not require any resistive termination. The LO power is divided with the required 90^0 phase delay by a waveguide branch-line coupler.

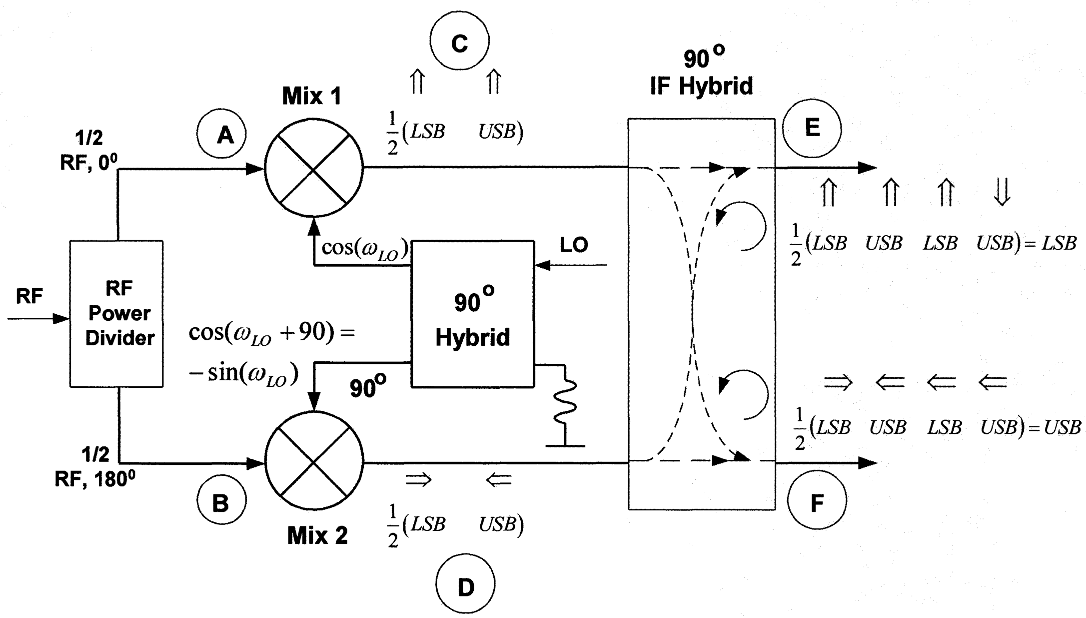

Figure 2 Block diagram of the suggested sideband separating mixer. To illustrate the sideband cancellation, the relative phases of the sideband signals at IF are shown at different points of the mixer. USB and LSB stand for Upper and Lower Side Band respectively.

Image products termination at RF

The output spectrum of a mixer excited with RF signal and pumped by a LO contains linear combinations of both frequencies. One of these combinations is an image component at RF. For example RF signal with frequency LO+IF will produce, through higher order conversion terms, a component with image frequency LO-IF. The way these combinations of frequencies are terminated by the mixer embedding circuitry is relevant to the conversion gain of the mixer.

In the case of a 2SB mixer using a four-port structure to divide the RF (Figure 1), these RF image components are dissipated at the input of the mixer. To illustrate how the corresponding image components are terminated in the suggested mixer design in Figure 2, we give an example by considering the RF image products produced by a third order conversion term.

<u>RF image products from Mixer 1</u>

$$[\cos(RF)+\cos(LO)]^3 = \cos(RF)^3 + 3\cos(RF)^2\cos(LO) + 3\cos(RF)\cos(LO)^2 + \cos(LO)^3$$

The second term produces components with frequency LO±2IF, while the third term is responsible for the image components at RF. For example if the signal is in the USB we have:

$$\cos(LO+IF)\cos(LO)^2 = \cos(LO+IF)[1+\cos(2LO)]$$

producing a component

$$\cos(LO+IF-2LO) = \cos(LO-IF), \qquad (1.1)$$

which is a frequency in the LSB (an image product).

In the same way if the signal is in the LSB:

$$\cos(LO-IF)\cos(LO)^2 = \cos(LO-IF)[1+\cos(2LO)]$$

producing a component

$$\cos(LO-IF-2LO) = \cos(LO+IF) \qquad (1.2)$$

which is also an image product.

<u>RF image products from Mixer 2</u>

Since the RF is applied to the mixers with 180^0 phase difference and the LO is delayed with 90^0 we have:

$$[-\cos(RF)-\sin(LO)]^3 = -\cos(RF)^3 - 3\sin(LO)\cos(RF)^2 - 3\sin(LO)^2\cos(RF) - \sin(LO)^3$$

The corresponding image components are: For signal in the USB

$$-\sin(LO)^2\cos(LO+IF) = -[1-\cos(2LO)]\cos(LO+IF)$$

giving rise to a component in the LSB

$$\cos(2LO-LO-IF) = \cos(LO-IF). \qquad (1.3)$$

If the signal is in the LSB:

$$-\sin(LO)^2\cos(LO-IF) = -[1-\cos(2LO)]\cos(LO-IF)$$

giving rise to a component in the USB:

$$\cos(2LO-LO+IF) = \cos(LO+IF). \qquad (1.4)$$

From the calculations above it follows that the considered image products at RF from both mixers are applied in *phase* to the outputs of the RF power divider (equations 1.1≡1.3 and 1.2≡1.4). Since the divider intrinsically produces 180^0 phase difference [5], *the same phase difference* is required to combine the image products and couple them to the input RF waveguide. Furthermore because the RF image components from both mixers are applied in phase, they will be reactively terminated in the structure and will not propagate in the input waveguide, i.e., the mixer behaves as an "image-enhanced" mixer where the image port is reactively terminated.

Mixer Design

The mixer block layout shown in Figure 3 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.

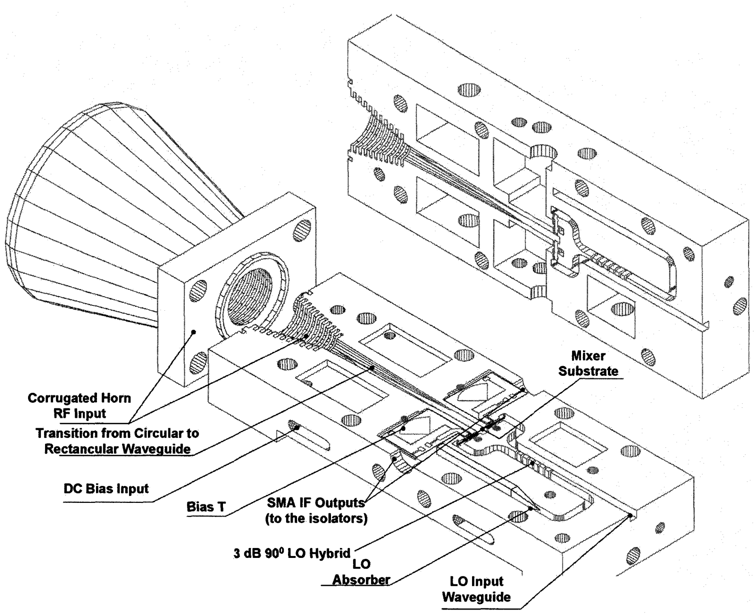

Figure 3 Layout of the sideband separating mixer. The mixer block consists of two identical parts dividing symmetrically all waveguide structures. Waveguide cross-section is 1.2/2.4 mm.

A closer look at the mixer substrate is presented in Figure 4. 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. The waveguide to microstrip double probe transition 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 [6].

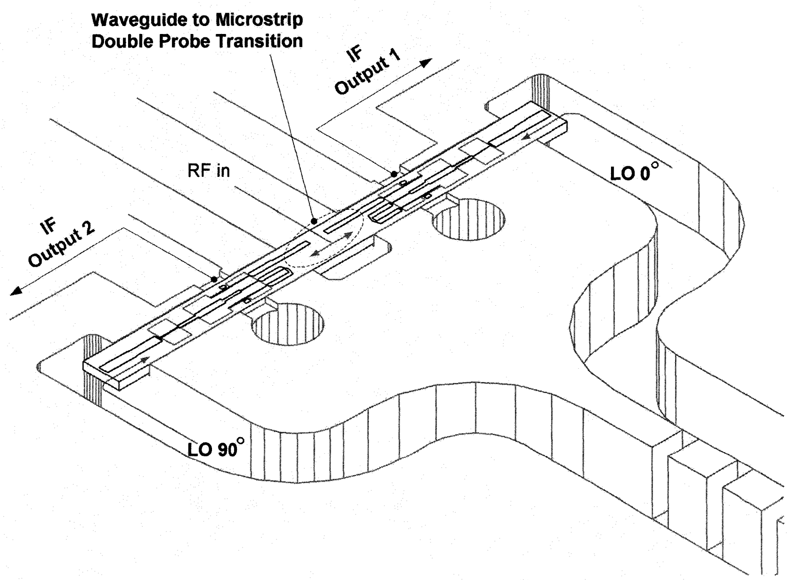

Figure 4 The mixer substrate coupled to the waveguides. The divided LO power is introduced at the ends of the substrate while the RF power is coupled to the substrate in the middle and divided between the two mixer junctions by the waveguide to microstrip double probe transition. The mixer substrate 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.

The divided LO power is coupled at the end of the substrate via an E-probe and transmitted to the 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 Figure 6.

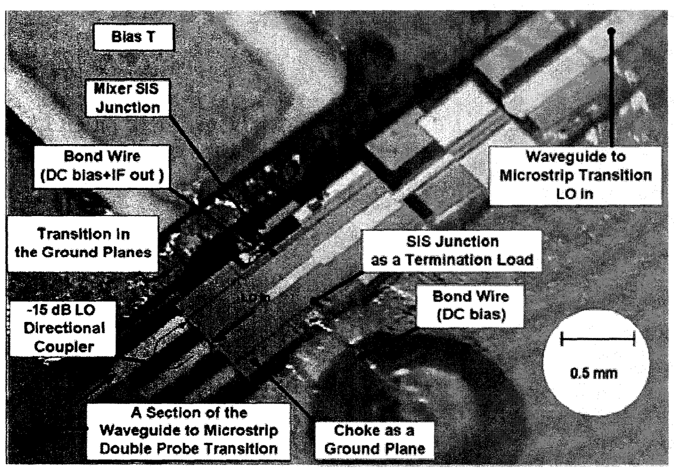

Figure 5 A closer view of the mixer components. In order to minimize the loss of RF power, the LO is injected to the RF line through a -15dB directional coupler. A second SIS junction and its tuning circuitry provides real impedance to terminate the rest of the LO at the idle port of the LO coupler. 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.

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 [6] 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.

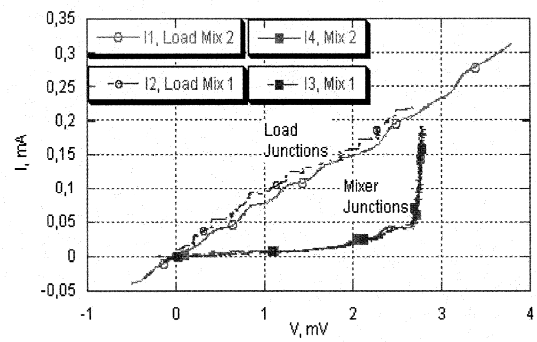

Figure 6 Junctions I-V curves in presence of LO power. The mixer junctions are pumped with optimum power for best sensitivity, while load junctions are over pumped being exposed to 15 dB higher power. The pairs of I-V curves show excellent symmetry giving good prospects for high degree of sideband separation.

Measurements

In order to characterize the 2SB mixer we measure the equivalent mixer noise temperature as a function of LO frequency using conventional Y-factor technique. In contrast to an ideal DSB mixer, a SSB mixer equivalent noise temperature T_{SSB} can not be measured without knowing sideband suppression ratios R_U, R_L. We calculate the T_{SSB} for USB and LSB using the T_{DSB} noise temperature derived from Y-factor measurements of the 2SB mixer, and the measured sideband suppression ratios:

$$T_{SSB,USB} = T_{DSB}\left(1+\frac{1}{R_U}\right),\quad T_{SSB,LSB} = T_{DSB}\left(1+\frac{1}{R_L}\right)$$

Calculating the sideband suppression ratios requires measuring 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. Since real mm-wave mixers are not ideal, 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. 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. Our measurements show that the variation of R_U, R_L vs. IF frequency is in the range of 2-3 dB and can be related to asymmetry produced by the IF hybrid and cold amplifiers.

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 7, 8.

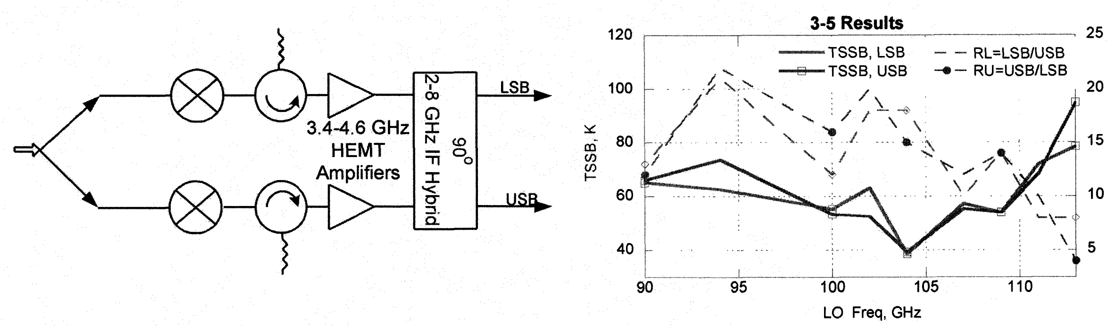

Figure 7 Measured SSB equivalent noise temperature T_{SSB} – solid lines, and sideband suppression ratios R_U, R_L-dashed lines vs. LO frequency, (equivalent to RF band of 86-118GHz with 4 GHz IF center frequency). IF band is 3.4-4.6 GHz and the IF hybrid follows the amplifiers.

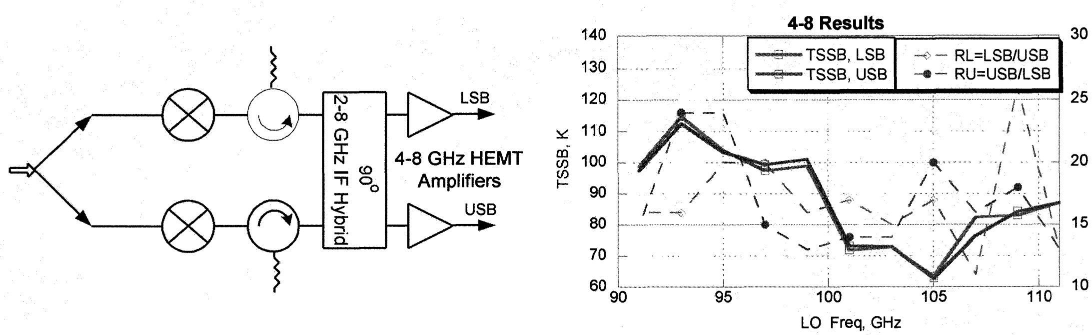

Figure 8 Measured SSB equivalent noise temperature T_{SSB} – solid lines, and sideband suppression ratios R_U, R_L-dashed lines vs. LO frequency, (equivalent to RF band of 85-117GHz with 6 GHz IF center frequency). IF band is 4-8 GHz and the IF hybrid is in front of the amplifiers.

Conclusions

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 7) 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 8) 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, partly because the IF hybrid, placed in front of the amplifiers, introduce some 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 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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