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A New Sideband Separation SIS Mixer for ALMA

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ABSTRACT

Single sideband fixed-tuned design, 8 GHz intermediate frequency band per polarization and state-of-art noise performance are the specifications for the SIS mixers to be used for receiver of Atacama Large Millimeter Array (ALMA). A quadrature sideband-separating scheme that uses two identical SIS mixers with the input signal divided equally between the mixers pumped by a local oscillator with 90° phase difference, is a good candidate to fulfill these requirements. This side-band separating mixer technology has been successfully demonstrated for mm-wave band [1, 2]. We introduce a new sideband separation mixer aimed for the ALMA instrument, band 7 (275-370 GHz). In the design we use a novel fixed-tuned waveguide-to-microstrip *double-probe coupler structure* that provides a broadband low-loss distribution of the input RF signal between the two quadrature SIS mixers. We present results of HFSS simulations and scale model measurements at 10 and 100 GHz for this key component of the new receiver, the double-probe coupler. The SIS mixers can be placed on the same substrate with their respective integrated tuning circuitry directly coupled to the waveguide via the probes.

Keywords: SIS mixers, millimeter-wave receivers, single side band, power divider, waveguide-to-microstrip transition

1. INTRODUCTION

With SIS mixer noise temperature approaching level of 2-5 times of quantum noise, hf/k, where f is operating frequency, h is Plank's constant and k is Boltsman's constant. The output noise of a double-side band (DSB) super-heterodyne receiver can be seriously degraded by the atmospheric noise coming into the system via the image band. In [3] Jewell and Mangum examine in details single versus double sideband operation in terms of the signal-to-noise ratio and optimum receiver performance. They found that SSB observations are more efficient not only for spectroscopic observations in one sideband, but even if spectral lines of interest are present in both sidebands. Thompson and Kerr [4] examine the relative sensitivities of single and double sideband receivers versus atmospheric opacity for two atmospheric windows and different receiver noise temperatures.

Several sideband-rejecting schemes allow achieving the desirable improvement in the signal-to-noise ratio for mixers used for millimeter radio astronomy, e.g., ***i.*** a mixer tuned for single sideband (SSB) operation with adjustable backshort [5], this method works for frequencies up to about 300 GHz and relatively narrow IF band but becomes impractical for higher frequencies due to difficulties in achieving a good Q-factor of the backshort tuning circuit; ***ii.*** a double sideband mixer with a rejecting filter (e.g., tunable interferometer) at the input, to filter out the image channel [6]; ***iii.*** a sideband separation mixer using quadrature scheme with two identical DSB SIS mixers pumped by a local oscillator (LO) with 90° phase difference. The main advantage of the latter solution is that with a fixed-tuned mixer no further tuning is required for SSB operation compare to the other designs. The upper (USB) and the lower sidebands (LSB) are available simultaneously at the two outputs and this relaxes the ALMA requirement of having 8 GHz wide IF frequency band, allowing to use a sum of 4 GHz-band USB and LSB.

The scheme of a side-band separation mixer is presented in Figure 1: the input RF signal is divided and distributed between the two identical DSB mixers, the LO power is also divided and coupled to the mixers with 90° phase difference. The IF outputs of the two mixers are connected to an IF quadrature hybrid, thus the down-converted USB and LSB signals appear separately at the two output ports of the hybrid. This approach requires effective, low-loss and wide-band power division between the mixers for the RF and the LO signals. Such a power splitting can be provided either in the waveguide (magic T) [1] or using a substrate with planar line structure (branch-line coupler, Wilkinson power divider) [2, 7].

The signal and the LO amplitude and phase *balance* at the two mixers is important [7] to obtain required sideband separation of the image channel over the operating band (more than 10 dB is a typical specification). In the presented design based on the sideband separation mixer scheme, we take advantage of a new device, a *double-probe coupler structure* that splits the input RF signal between the two ports with minimum losses over a wide frequency band and provides transition from waveguide to a microstrip line for easy integration of a SIS mixer.

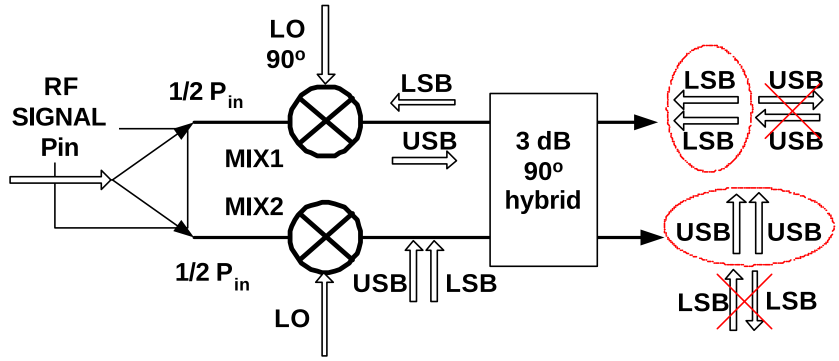
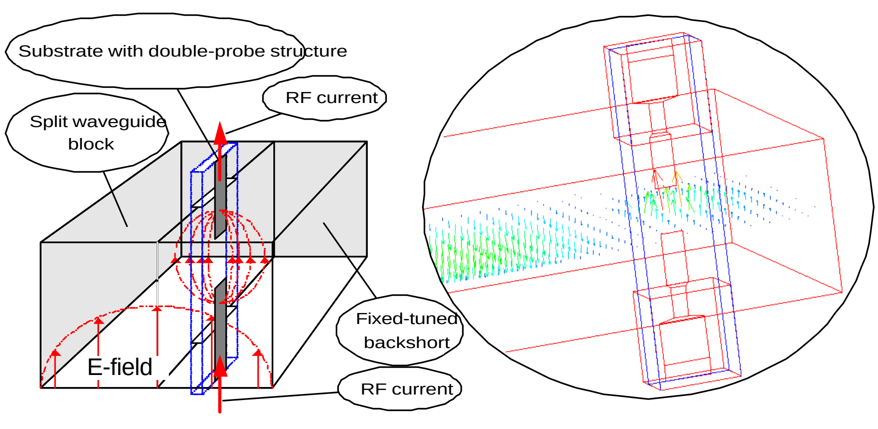


Figure 1. Block diagram of the sideband separation mixer. The crossed out items at the hybrid outputs are the rejected sidebands (180° phase difference).

2. SIDBAND SEPARATION RECEIVER DESIGN

The SSB mixer (Figure 1) requires relatively complex signal and LO distributing circuitry: the input signal and the LO power have to be divided symmetrically with minimum losses over the operating frequency band. Most of the existing power-dividing schemes used for microwave applications are relatively difficult to implement at 300 GHz. For example, if a branch line coupler is used several branch sections have to be cascaded in order to provide the required amplitude symmetry over the entire band. This may complicate the design and also requires a planar terminating resistor that, with necessary tolerances, is difficult component for a thin-film processing. Waveguide type couples have impractically small dimensions for 275-370 GHz frequency band to use conventional split-block technique with critical constrains on the tolerances required from the machining.

In our design, for distributing of the input signal, we take advantage of a *novel* power divider, a *double-probe coupler structure*, which consists of an input waveguide with a substrate penetrating the waveguide through symmetrical slots in the middle of the broad wall as shown in Figure 2. The double-probe coupler uses *two symmetrical planar probes* coupled to the electromagnetic field in the waveguide instead of a *single-probe* in a waveguide-to-microstrip transition used in the previously reported mm and sub-mm mixers [8 - 11]. The substrate with the probes is placed in the waveguide at a quarter of wavelength distance from the backshort; E-field excites anti-symmetric RF currents (180° phase difference) in the two probes.



(a) (b)

Figure 2. (a) The double-probe structure patterned on a substrate crosses the waveguide broad wall in the middle; (b) simulated E-field distribution for the double-probe coupler.

The substrate dimensions are chosen based on two considerations: ***i.*** to prevent waveguide mode propagation inside the substrate channel the dimensions of the substrate should be sub-critical; ***ii***. to provide enough mechanical stability for multi-step processing of the double-probe coupler and the SIS mixers.
With this approach we are able to use conventional split-block technique and machining to fabricate the mixer mount. The probes and the SIS mixers are fabricated on the same substrate using thin-film processing technique. This allows very accurate (at micron scale) patterning of the probes using photolithography and the design can be scaled further up in the frequency. The layout of the sideband separation mixer based on the double-probe coupler would look as it is depicted in Figure 3.

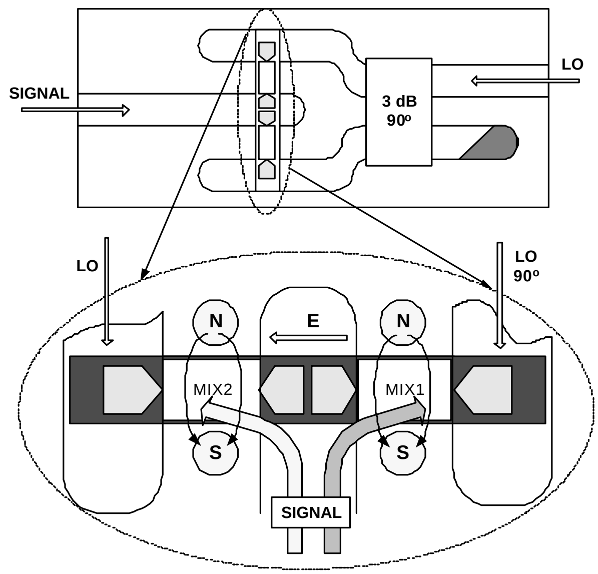


Figure 3. *On the top:* The layout of the sideband separation receiver employing the double-probe coupler; *on the bottom:* the substrate with the two-probe coupler, the two SIS mixers and the single-probe LO injecting feeds.

Placing the mixers relatively distant from each other allows individual magnetic field feed for each mixer to suppress Josephson current and that is extremely important to achieve ultimate performance of the mixer. LO injection is provided via the two single-probes (waveguide-to-microstrip transitions) placed on the edges of the substrate coupled to the LO-feeding waveguides. The LO feed waveguide can be equipped with *in situ* adjustable attenuator and phase shifter for individual tuning of the LO power and LO phase for each SIS mixer.

3. WAVEGUIDE-TO-MICROSTRIP POWER DIVIDER WITH DOUBLE – PROBE COUPLER

The mixer input circuitry loss and in particular the loss in the waveguide-to-microstrip transition has major influence on the mixer noise performance. In order to minimize the input losses of the proposed sideband separation mixer, the double-probe coupler has been carefully studied and several stages of optimization have been done. The probe shape, position on the substrate and the substrate location in the waveguide were optimized; the optimization was focused on four main characteristics of the double-probe coupler, namely, the operating frequency band (275-370 GHz yields $f_{max} / f_{min} = 1.345$), the insertion loss, the input port matching and minimum possible coupling between the output ports. The double-probe structure has been simulated using high frequency structure simulator (HFSS) software [12] employing the finite element method. The separation between the probes has been found to be a significant factor for obtaining minimum losses. Scaled modeling has been used for accurate characterization of the double-probe coupler at 10 GHz and at 100 GHz using network analyzer [13].
To perform measurements at 10 GHz with the network analyzer that uses standard SMA 50 Ω connector we integrated the connectors at the outputs of the scale model device. The probes, placed in the middle of the broad wall of the waveguide, as shown in Figure 4, represent a capacitive reactance; the inductive lines following the probe transform the real part of the impedance to 50 Ω at the center frequency of the band. The substrate made of crystal quartz is oriented in the longitudinal direction with respect to the waveguide and benefits no radiation from the waveguide block joint. Since the dimensions of

the waveguide at millimeter wave frequencies become small, the waveguide is designed with curved backshort corners in order to facilitate the machining of the 300 GHz device. If properly designed, the curved backshort can even increase the bandwidth of the coupler. The E-field for the dominant TE_{10} mode has its maximum at the center of the substrate at equidistant point from the probes. The E-vector oscillates in the direction that is parallel to the probes orientation inducing anti-symmetrical currents (Figure 2).

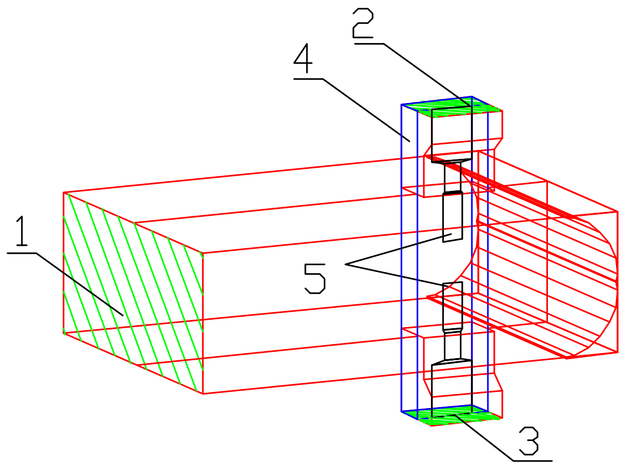
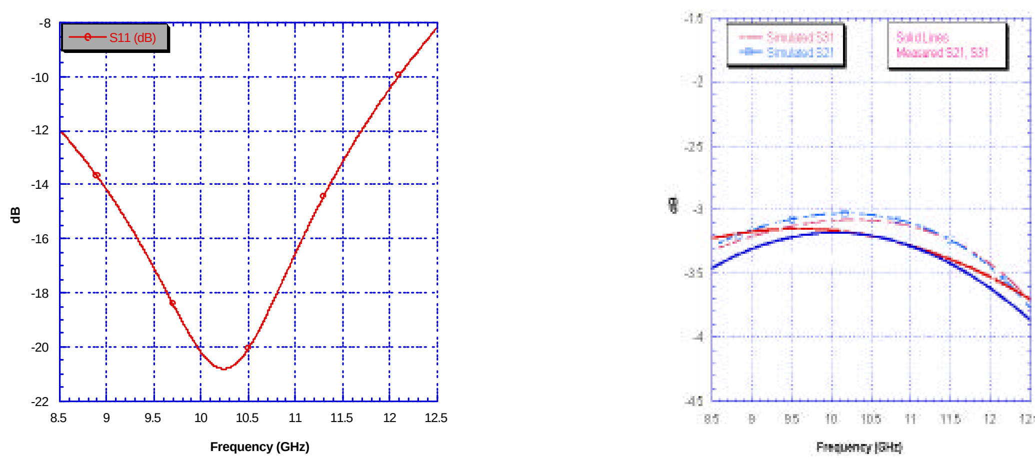


Figure 4. The scale model at 10 GHz. 1 - the input waveguide port (WR-90), 2, 3 - microstrip output ports (to be connected to SMA with room to accommodate the connector lead), 4-the channel with the substrate, 5-photolithography-patterned double-probe structure.

As we mentioned above, the 10 GHz scale model uses standard SMA 50 Ω connector to connect the output ports to the network analyzer. Our HFSS simulation comprises the connectors and microstrip-to-coaxial line transition (not shown in Figure 4). The overall performance of the double-probe coupler was affected by these additional elements, which results in slightly lower S21 and S31 towards the band sides, especially towards the higher frequencies. The measured and simulated performance depicted in Figure 5 is in a very good agreement with small discrepancy of 0.2 dB in the middle of the band.



(a) (b)

Figure 5. The scale model at 10 GHz. (a) Simulated S11; (b) Simulated transmission - dashed lines, measured transmission – solid lines.

The double-probe coupler is a perfect phase-splitter: since the E-field vector oscillates in the direction parallel to the probes, the phase difference of 180° for all frequencies is introduced between the output ports of the device (Figure 6).

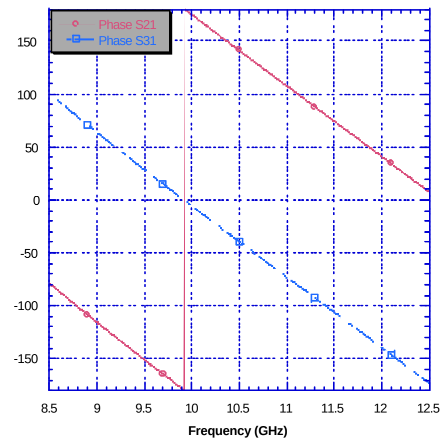


Figure 6. Simulated phase at output ports of the double-probe coupler.

The result of this 180° phase difference introduced by the double-probe coupler for the sideband separation mixer (as long as it is constant over the pass-band) is that a pair of vectors, at the output of one of the mixers shown in Figure 1, will be shifted to 180°, which will not affect the performance of the SSB mixer. The only change is that the USB and LSB will swap their location at the outputs of the 90° hybrid.

4. DOUBLE-PROBE COUPLER AT 100 GHZ

The sideband separation receiver (Figures 1 and 3) should comprise on one substrate the double-probe coupler, the two SIS mixers and the LO feed circuitry with the single-probe couplers at the edges of the substrate. We use a scale model at 100 GHz to check more elements of the suggested mixer layout. The device for 100 GHz, shown in Figure 7, consists of the double-probe coupler with its output ports connected to the two single-probe couplers via a tapered line so that we can verify and characterize most of the crucial embedding components of the SIS mixer. The 100 GHz device has only waveguide ports and this is convenient for the measurements using the scalar network analyzer with waveguide adapters.

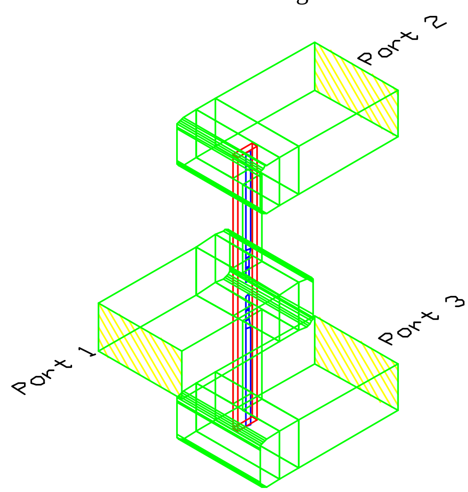
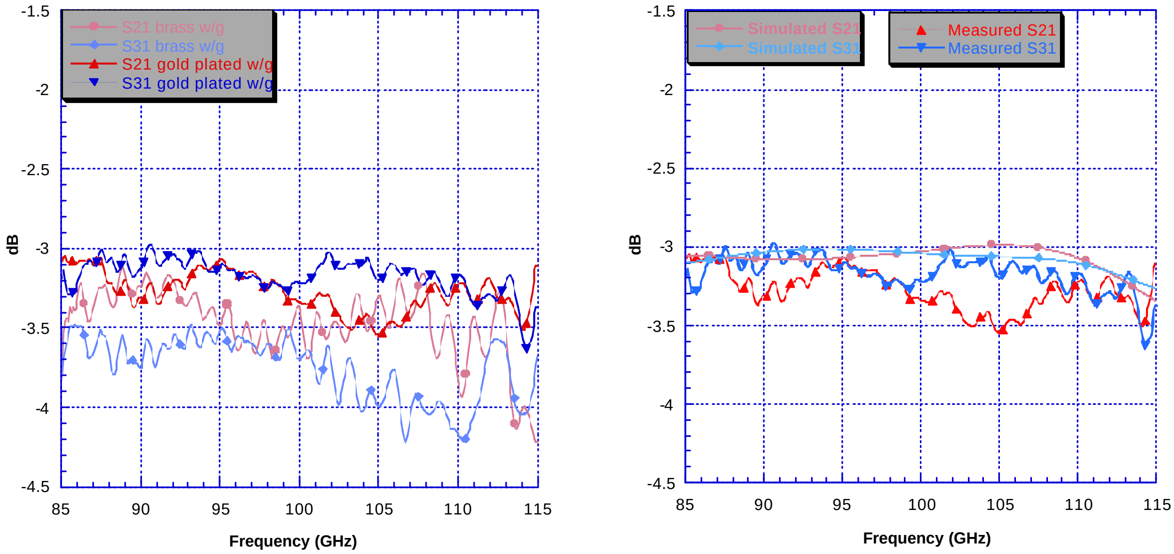


Figure 7. The scale model for 100 GHz: the waveguide-to-waveguide power divider comprises the double-probe coupler connected to the two single-probe couplers. The device uses WR-10 waveguide, the substrate dimensions are 7.27x0.61x0.15mm with the substrate channel 0.3mm deep. The input waveguide (Port 1) has length of 5 mm, while the two output waveguides (Port2, 3) are 40 mm long (truncated in Figure 7).

These relatively long waveguide feeds (Figure 7) contribute noticeably to the overall insertion loss. To get an idea about the insertion loss of the coupler we compared the measured S21 and S31 of the device with and without gold-plated waveguides, Figure 8a. From the figure we can see that the substantial part of the losses are due to loss in the input and output waveguides. The measured and simulated transmission of the structure shown above is depicted in Figure 8b.



(a) (b)

Figure 8. Scale model measurements at 100 GHz. (a) S21 and S31 of the device with and without gold-plated waveguide; (b) measured and simulated transmition, S21 and S31.

The result of the measurement shows typical insertion losses of 0.2-0.3 dB over 30% of the bandwidth including the loss in the waveguide. The maximum amplitude asymmetry is 0.3dB, which would hardly be a limiting factor for good image-band suppression (for reference, the amplitude imbalance of 1dB, with zero phase imbalance, results in image rejection of 25dB [7]). Comparison between the measured performance of the 10 GHz scale model (Figure 5b) and the 100 GHz model (Figure 8) shows better flatness in the transmition for the latter device. This can be explained by the fact that to perform the measurements at 10GHz we use SMA connectors; therefore, to match the real impedance of the structure, the inductive lines (90Ω) following the probes (Figure 4) are coupled to the lower impedance lines (50Ω). The difference of the impedances is relatively high and the result is a reduced bandwidth. At 100 GHz instead of the SMA connectors we use single-probe microstrip-to-waveguide transitions. In this case impedances are not so different, 90Ω and 75Ω, and thus the bandwidth is broader.

5. CONCLUSION

In this paper we presented a new design of the sideband separation receiver using a novel mm and submm wave device, fixed tuned *double-probe coupler structure*. The double-probe coupler is a waveguide-to-microstrip power divider that provides a broadband operation and has low insertion loss. The coupler has been modeled and its layout was optimized using HFFS electromagnetic simulation package. Scale model measurements of the coupler have been done at 10 GHz and at 100 GHz using network analyzer. We have achieved a very good agreement between the simulated and the measured performance with typical measured insertion loss of 0.2-0.3 dB at 85-115GHz and nearly negligible amplitude imbalance. The device is relatively simple and easy to scale for mm and submm wavelengths, compare to the conventional power dividers, which are more difficult to fabricate with required accuracy. The test structure for 100 GHz comprises all the main elements of the SIS mixer imbedding circuitry and has been proved to be a good candidate to use for the suggested sideband separation mixer. Such a power divider can be considered as a useful component for, e.g., LO feed system when one LO source is used for feeding two SIS mixers receiving orthogonal polarization or for a multi-channel receiver where all mixers share one LO source. We used the same type of device, as the described scale model at 100 GHz, to design LO feed system of 3 mm band SIS Radio Camera Receiver for Onsala Space Observatory.

6. ACKNOWLEDGEMENTS

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