Design of a side-band-separating heterodyne mixer for band 9 of ALMA.

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***Abstract*— A side-band-separating (SBS) heterodyne mixer has been designed for the Atacama Large Millimeter Array (ALMA) 602-720 GHz band, as it will present a great improvement over the current double-side-band configuration under developed at the moment. Here we present design details and the results of extensive computer simulations of its performance. The designed SBS mixer exploits waveguide technology. At its core it consists of a quadrature hybrid, two LO injectors, and three dumping loads. The entire structure has been analyzed in a linear circuit simulator with custom code written to accurately (verified by HFSS finite element simulations) model the hybrid structures. This technique permitted an optimization of the dimensions and the study of the consequences of deviations from the ideal situation. It is estimated that the tolerances in several of the components should be kept at less than 3 μm. Important parts of the design are the dumping loads which, due to the involved dimensions, are not easy to implement. Therefore, we have also designed a simple load which is rather large compared with the waveguide making it relatively easy to realize at such small dimensions. It consists of a large cavity at the end of the waveguide and filled with an absorbing material. A simulation of its performance shows that besides its simplicity it can have a reflectivity as low as -40 dB if the appropriate material is used.**

I. INTRODUCTION

A well known improvement over double-side-band (DSB) mixers is the side-band separating (SBS) configuration. Contrary to to the DSB mixers, the later permits the separate detection of the upper and lower RF band frequencies. Despite this important advantage, it is not always implemented at high frequencies as the involved dimensions for the required components are prohibitory small. This is particularly true in the range corresponding to ALMA band 9 (602-720 GHz) and, hence, DSB mixers are currently being developed. However, the current state-of-the-art technology is such that, we believe, it will permit the implementation of SBS heterodyne mixers at even these high frequencies. We, therefore, have designed a heterodyne mixer in the SBS configuration containing a quadrature hybrid. The proposed waveguide structure has been extensively modeled assuming perfect load terminations. This modeling has permitted an optimization of the structure dimensions for the range corresponding to ALMA band 9. Deviations from the optimal dimensions have also been studied, which suggest that for a good performance the tolerances of several of the components have to be kept at around 3 μm. Moreover, in this article, we also propose a new design for the waveguide termination loads that will be an important component of the hybrid mixer. A new design for the loads is necessary due to the small dimensions involved. We show that with this new design a reflectivity as low as -40 dB can be achieved if the appropriate material is used.

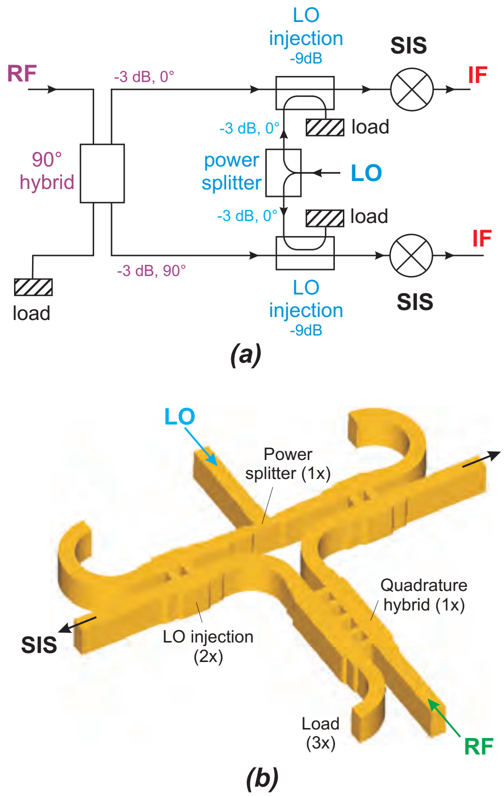

Fig. 1. *(a)* Diagram of the chosen configuration for a SBS mixer. *(b)* Core of the proposed waveguide implementation. The transversal dimensions of the waveguide are 145×310 μm.

II. DESIGN

A. Quadrature Hybrid

A layout of the chosen configuration and the proposed implementation for the SBS mixer are shown in Fig. 1. The core of the suggested mixer consists of a quadrature hybrid, two LO injectors, and three dumping loads. Although a balanced

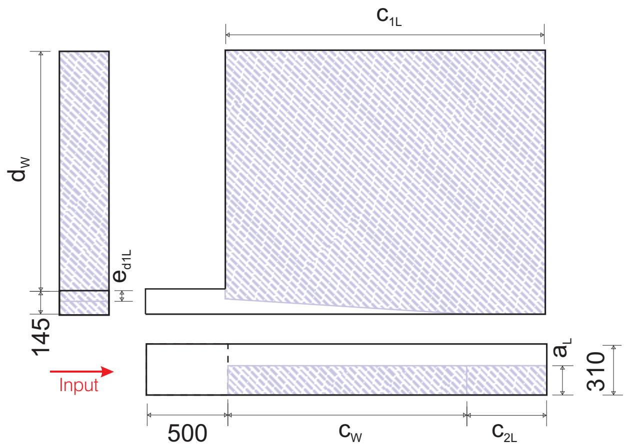

Fig. 2. Proposed design for a waveguide load (all dimensions are in μm). At the end of the waveguide, a large cavity is built which, in turn, is partially filled with an absorbing material (gray lines). The figure also shows the parameters that have been changed during the simulations.

TABLE I

PARAMETERS OF THE LORENTZ OSCILLATOR USED TO SIMULATE THE TRANSMISSION DATA OF REF. [2].

ϵ_∞	ω_o	ω_p	γ
-	GHz	GHz	GHz
4.2	15300	14220	207900

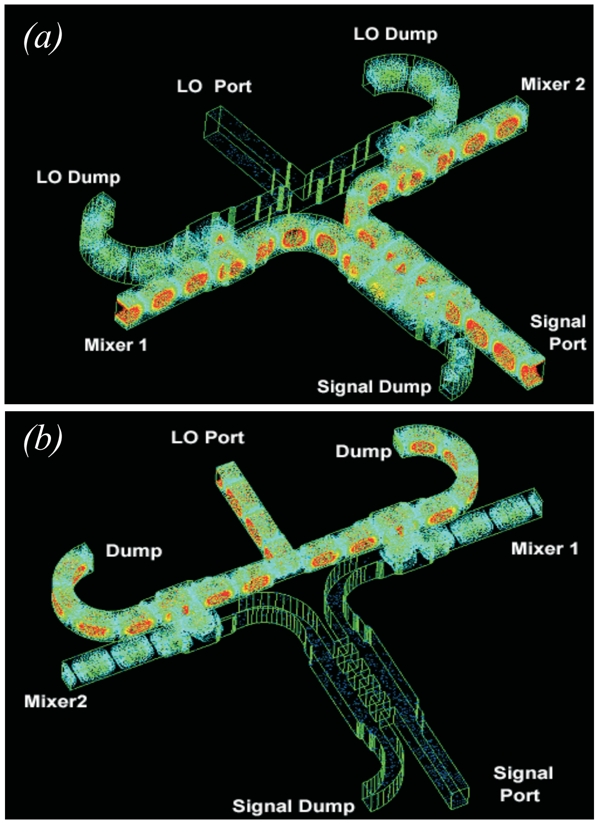

Fig. 3. *(a)* Electric field distribution with the signal port excited. The input signal is split 50% with a 90° phase difference between the two output ports. By design approximately 10% of the LO signal is coupled into the signal path. *(b)* Electric field distribution with the LO port excited. Approximately 10% of the available LO power couples to the mixer path, with the remaining 90% of the LO terminated. In both cases the simulation frequency is 660 GHz.

mixer containing a 180° hybrid has superior fundamental and intermodulation product suppression capabilities, its 90° counterpart is simpler and, thus, easier to implement at this frequencies [1].

B. Load

The load presented here consists of a cavity at the end of the waveguide and which is partially filled with an absorbing material. The design is depicted in Fig. 2 where the space filled with the absorbing material is represented by gray lines. This geometry should be relatively easy to make as the the largest dimensions are designed to be parallel to the splitting plane of the block. Moreover, the dimensions of the load itself are suitable to be machined by conventional means.

One candidate to be used as absorbing material is the commercially available epoxy MF112 [2], [3]. From published transmittance data [2], we have modeled its dielectric function in this frequency range with one Lorentz oscillator [4]. The corresponding parameters (presented in Table I) were used in the simulations presented in the following section.

III. SIMULATION AND RESULTS

A. Quadrature Hybrid

The construction presented in Fig. 1 has been analyzed in a linear circuit simulator with custom code written to accurately model the hybrid structures. The results were verified by HFSS finite element simulations. This has the advantage that the effect of non-ideal termination impedances may be examined. In the ideal situation, the SIS junctions are well matched to the probe impedance and the waveguide terminations are ideal. This maybe regarded as an ”upper performance limit”. In the non-ideal situation the port mismatch is chosen to be 25% (-12 dB return loss).

The results of the simulations are summarized in Figures 3 through 5. First, to illustrate how the various components of the proposed hybrid perform in the ideal situation, in Fig. 3 we show the electric field distributions when *(a)* the signal and *(b)* the LO ports are excited independently. In the former case, the input signal is split 50% with a 90° phase difference between the two output ports. By design approximately 10% of the LO signal is coupled into the signal path, and it follows from reciprocity that 90% of the signal will couple to the LO path (dump). The loss of 10% was deemed acceptable. When the LO port is excited, approximately 10% of the available LO power couples to the mixer path, with the remaining 90% of the LO terminated. It has to be noted that the device will operate at 4 K.

Figure 4 shows the sideband rejection ratio in the ideal (upper limit) and non-ideal situations (lower limit). Note that the latter case although includes power and phase imbalances, it does not include IF and mixer gain imbalances. Finally,

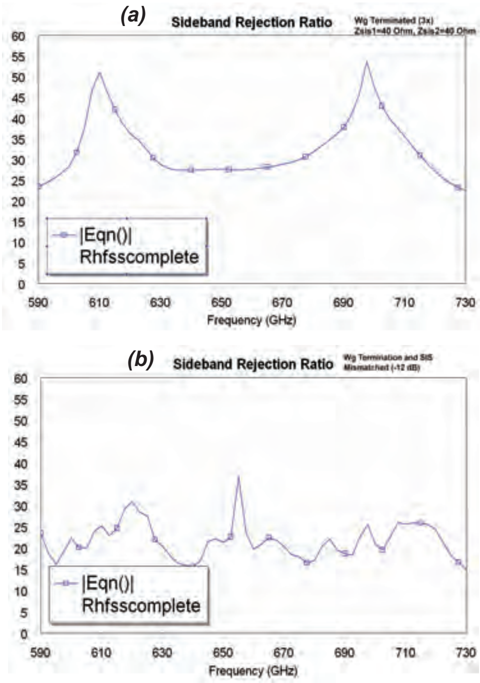

Fig. 4. Sideband rejection ratio in the *(a)* ideal and *(a)* non-ideal situations. In the non-ideal scenario, the SIS junction and waveguide termination are presumed to be mismatched by 25% (Return loss = -12 dB). The results include power and phase imbalances, however do not include IF and mixer gain imbalances.

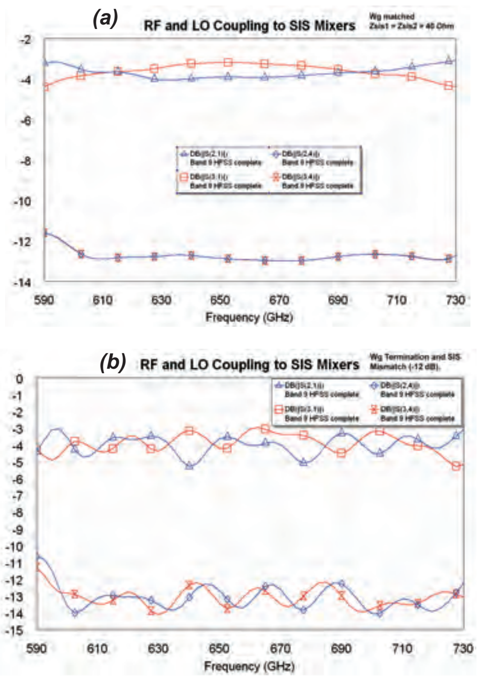

Fig. 5. RF and LO coupling to the SIS junctions in the *(a)* ideal and *(b)* non-ideal cases.

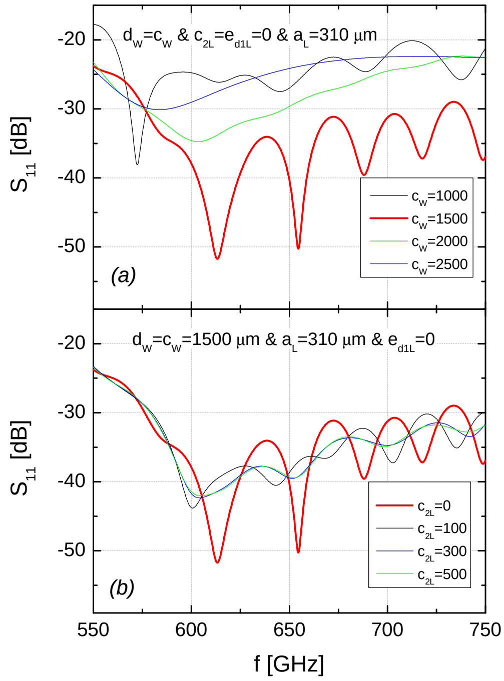

Fig. 6. Resulting S_{11} coefficient when the dimensions *(a)* c_W and *(b)* c_{2L} are varied.

Fig. 5 presents the RF and LO coupling to the SIS junctions in both cases. The LO power coupling balance is critically dependent on both LO dumps having the same termination impedance. In turn this will affect the pumping level of the individual mixers and their mixer gain (mixer gains ought to be closely matched).

B. Load

The one-port system depicted in Fig. 2 was simulated in CST Microwave Studio [5] with the load material simulated according the parameters given in Table I. The geometrical parameters varied during the simulations are length of the load cavity (c_W), cavity width (d_W), height of the load (a_L), and matching between the waveguide and the load material (e_{d1L}). All of them are also shown in Fig. 2. In the first place, by varying c_W and d_W (with $a_L = 310$ and $c_{2L} = e_{d1L} = 0$), we have found that the overall lowest reflectivity is achieved when $c_W = d_W = 1500$ μm (Fig. 6a). At that values, the reflectivity shows a series of oscillations that are rapidly *washed out* by increasing c_{2L} (Fig. 6b).

Our load design is prone to two kinds of errors, air gaps ($a_L < 310$ μm) and geometrical mismatches between the waveguide and the load ($e_{d1L} \neq 0$). These errors have been simulated and the results are presented in Fig. 7a. The load performance is not degraded substantially in the presence of large air gaps. As shown in Fig. 7a, a gap as large as half the waveguide height, still produces a reflectivity bellow -20 dB. Regarding the geometrical mismatch e_{d1L}, small changes

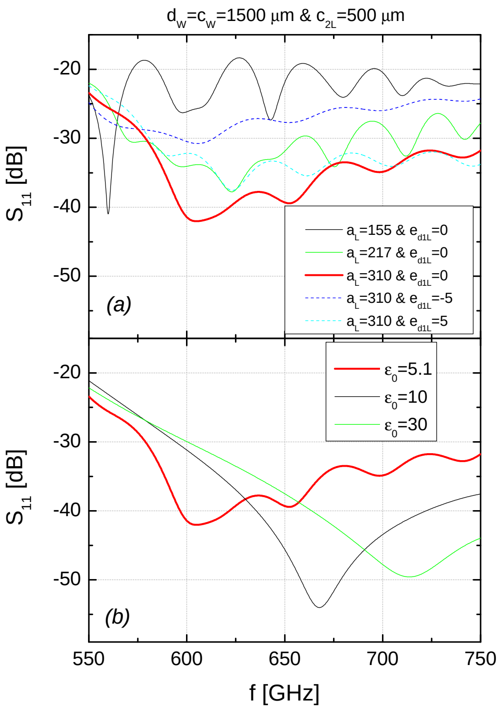

Fig. 7. Simulation of the load performance when : *(a)* mounting errors ($a_L < a$; $e_{d1L} \neq 0$) are present and *(b)* different materials are used.

in both directions produce a rather large degradation of the performance of the load. However, errors as large as 20 μm produce still a reflectivity below -20 dB (not shown here).

Finally, we have modeled the performance of the load with different materials. This have been simulated by changing the Lorentz model given in Table I. The specific parameter changed is the static value of the dielectric function ($\epsilon_0 \equiv \epsilon(0) = \epsilon_\infty + \frac{\omega_p^2}{\omega_0^2}$). Fig. 7b shows the results that demonstrate the ability of our design to perform efficiently with a wide range of materials.

IV. Conclusions

In conclusion we have presented a design for a side-band-separating mixer for the frequency region corresponding to ALMA band 9. Its ideal and non-ideal properties have been presented from which it is estimated that tolerances in some of the components should be as low as 3 μm. We think these tolerances are achievable with state-of-the-art micromachining, which is confirmed by the first promising attempts [6]. A design of a new load has also been presented. Its relatively large dimensions respect to the waveguide make it appropriate for high frequencies. Moreover, the results of the simulations indicate that the design is very robust as can tolerate rather large mounting errors and a wide variety of absorbing materials.

References

[1] J. W. Kooi, A. Kovacs, B. Bumble, G. Chattopadhyay, M. L. Edgar, S. Kaye, R. LeDuc, J. Zmuidzinas, and T. G. Phillips, *Heterodyne Instrumentation Upgrade at the Caltech Submillimeter Observatory*.

[2] G. A. Ediss, A. R. Kerr, H. Moseley, and K. P. Stewart, ”FTS Measurements of Eccosorb MF112 at Room Temperature and 5 K from 300 GHz to 2.4 THz”, ALMA Memo 273, 2 September 1999.

[3] http://www.eccosorb.com/.

[4] F. P. Mena and A. Baryshev, ”Design and Simulation of a Waveguide Load for ALMA-band 9”, ALMA Memo 513, 5 January 2005.

[5] http://www.sonnetusa.com/.

[6] Private communication, Radiometer Physics GmbH, http://www.radiometer-physics.de.