Waveguide Circuitry for the Prototype ALMA Band 6v2 Sideband Separating SIS Mixer

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***Abstract*—We describe the design and analysis of the waveguide circuitry proposed for the sideband separating (2SB) mixer of an upgraded ALMA Band 6 (Band 6v2) receiver. This unit, optimized for the 209–281 GHz Band 6v2, incorporates a waveguide quadrature RF hybrid, a cold termination for image frequencies, and an LO power splitter. It connects two Band 6v2 double sideband (DSB) SIS (Superconductor-Insulator-Superconductor) mixer modules to the input LO waveguide and the RF orthomode transducer. The output IF band is 4–16 GHz, with a goal of 4–20 GHz.**

The Band 6v2 2SB receiver must have a sideband rejection ratio (SRR) ≥ 15 dB over 90% of the bandwidth. Multiple reflections between the RF hybrid, LO splitter, image termination, and the DSB SIS mixer modules contribute to the SRR degradation. We use an analytical procedure to predict the contribution of the RF hybrid and LO couplers to the SRR.

The component waveguide branch-line RF hybrid was independently fabricated as a test module and characterized using a vector network analyzer (VNA). Simulated and measured results of the coupling, phase and amplitude balance, and return loss of the quadrature RF hybrid are presented along with their predicted contribution to the SRR.

***Keywords*—2SB, RF hybrid, SRR, 4K image termination.**

I. Introduction

Sideband separating SIS mixers, used in most ALMA receiver front ends, help to minimize the single sideband (SSB) system noise by reducing the atmospheric noise contribution from the unwanted image sideband. The Band 6v2 prototype receiver is based on a compact design in which two DSB SIS mixer chip modules are connected to the sideband separating waveguide module (2SB module assembly) along with the superconducting electromagnet used to suppress Josephson currents in the SIS junctions. The 2SB module assembly is an E-plane split block containing a 3-dB quadrature RF hybrid, 4-K image termination, and an in-phase LO power splitter. The ALMA Band 6 Wide Sensitivity Upgrade (WSU) receiver upgrade specifications require RF coverage to be expanded from the current 211-275 GHz to 209-281 GHz, and the SRR to be increased from ≥ 10 dB to ≥ 15 dB over 90% of the band [1].

To meet the new bandwidth and SRR specifications, the 2SB assembly has been designed with a layout which minimizes its size and insertion loss. This paper describes the design of the RF hybrid and the LO splitter. The full 2SB mixer module has a non-standard interface, therefore, it does not lend itself to direct testing with a VNA. We therefore used a test module with RF hybrid identical to that in the 2SB module but with accessible waveguide ports for connection to a VNA. The waveguide size WR-3.7 (0.0185” x 0.037”) supports TE_{10} single mode propagation throughout the 209–281 GHz operating band. The SRR of the 2 SB assembly was calculated from measured RF hybrid data and using the analytical model described in [2].

II. Design of 2SB Module Assembly

The new 2SB module is shown in Fig. 1. The quadrature RF hybrid and the LO splitter waveguide structure is shown in Fig. 2. They were designed with electromagnetic field simulation in CST Studio Suite [3].

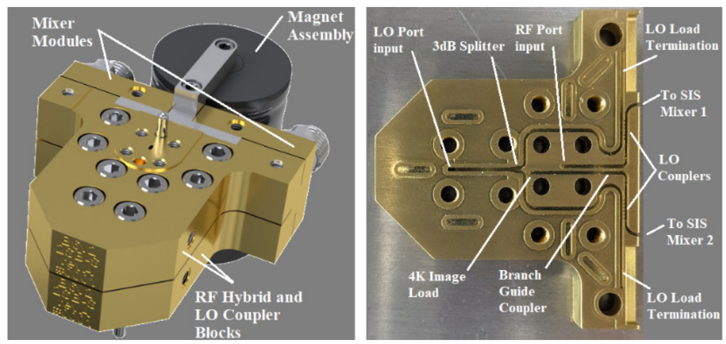

Fig. 1: Left: 2SB assembly with two mixer modules and a superconducting solenoid attached. Right: View of one half of the split-block showing the waveguide circuitry, 4K image termination and waveguide ports.

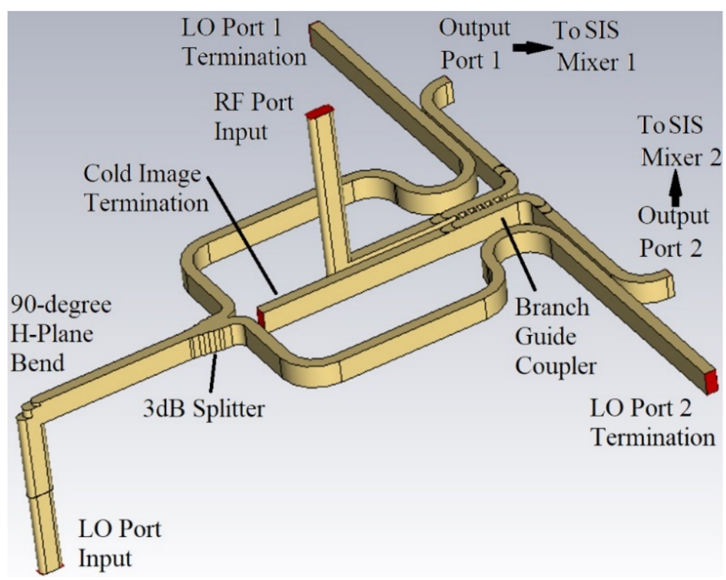

Fig. 2: The structure of the waveguide circuit of the 2SB module assembly simulated in CST Studio. The circuit includes the LO splitter, quadrature RF hybrid, and the 4K image termination.

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The E-plane branch-line coupler is designed following the approach in [4] so that power incident on any port is divided equally between two coupled ports with a 90-phase difference, while the fourth port is isolated. There is a plane of symmetry around the plane perpendicular to the broad walls of all the waveguides and intersecting them in the middle. As no currents flow across this plane of symmetry for the TE_{10} mode, imperfect contact between the two halves should not impact the performance of the circuit.

Details of the branch guide coupler are shown in Fig. 3. It consists of two WR-3.7 waveguides that start at full height (b = a/2) and then increase in height in two steps. There are six quarter-wave branch guides whose dimensions and separations are optimized to obtain 3 dB coupling over the entire RF band with an amplitude imbalance ≤ 1 dB and phase balance within 1.0°. The input of the branch guide coupler is connected to the WR-3.7 RF waveguide port via an H-plane 90-degree bend, while the two output waveguides are connected to the output ports with 90° E-plane bends. A wedge-shaped load of Eccosorb MF116 material, which has a minimum return loss of 35 dB across the RF band [5] is installed as the image termination for the 2SB mixer.

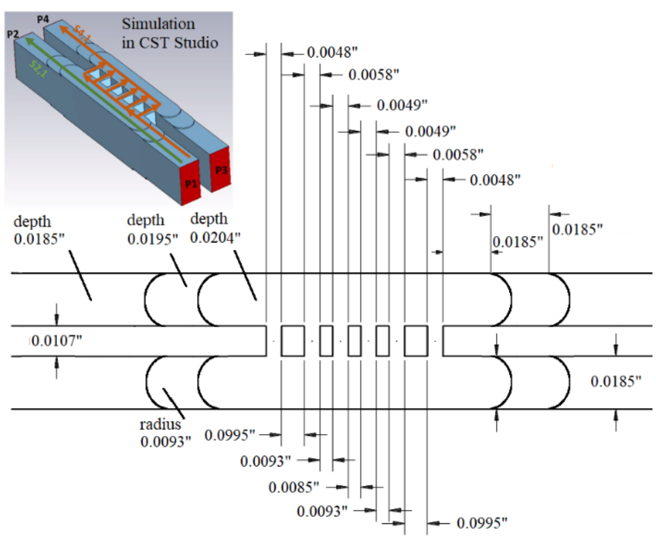

Fig. 3: The WR-3.7 quadrature hybrid consists of two parallel waveguides coupled through a series of six branch waveguides and fabricated as a split block structure. The lengths of the branch guides and their spacings are approximately a quarter of a guide wavelength at the center frequency of operation.

The electromagnetic field simulation of the LO power splitter is described in [6]. For the present application in the 2SB assembly, we have added an H-plane 90-degree bend followed by a two-stage transition from WR-3.7 to the WR-3.4 (0.034" x 0.017") LO input port.

The LO power is coupled into the RF signal waveguides through directional couplers as shown in Fig. 4. Each coupler has six gold plated coupling probes between the two waveguides similar to the one described in [7]. The probes are 0.004" wide x 0.010" long x 0.001" thick and are supported on fused quartz standoffs 0.004" x 0.004" x 0.003" high in channels 0.004" long x 0.010" wide x 0.008" high.

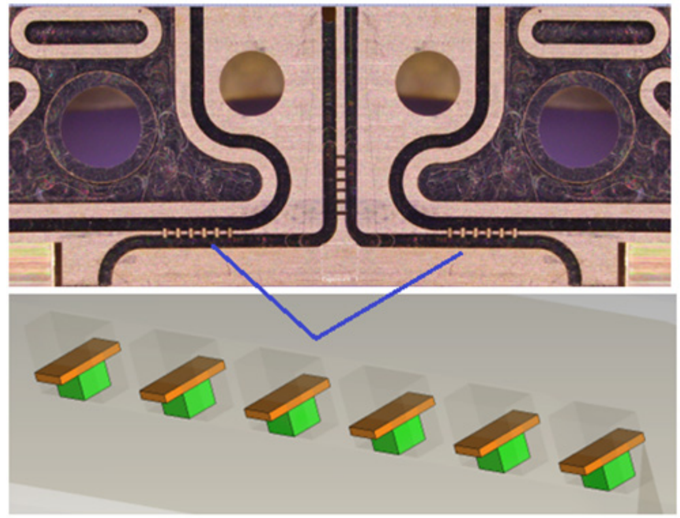

Fig. 4: Photograph shows a section of the branch guide coupler and the two sets of LO coupling waveguide channels. The bottom picture shows the CST simulation of the coupling of six gold probes on quartz standoffs inside each set of the LO coupling waveguide channels.

The coupling of the LO to the two output ports was simulated using CST Microwave Studio [3] and found to be 22.9 ± 1.0 dB across the RF bandwidth. Table I shows the simulated performance characteristics of the complete 2SB module assembly.

TABLE I.

Frequency Range	209-281 GHz
Amplitude Imbalance, max	0.60 dB
Phase Imbalance, max	+/-0.59°
Port Return Losses	≥ 19 dB
Isolation	≥ 22.5 dB
Sideband rejection Ratio	≥ 27.5 dB
LO to RF Coupling	-22.9 ± 1.0 dB
Excess Insertion Loss, Cold	≤ -0.21 dB
Excess Insertion Loss, T=298K	≤ -0.45 dB

The sideband rejection ratio of the 2SB module is simulated using the approach taken in [2], which includes the effect of multiple reflections inside the module. The SRR is not only affected by the phase and amplitude imbalance of the individual components, but also by two reflection mechanisms interfering inside the 2SB module: (1) reflections from the output ports pass back and interfere at the imperfect 4K load termination inside the isolated port as illustrated in Fig. 5(a), and, (2) reflections at the two output ports due to input return loss of the mixers and the finite isolation of the quadrature RF hybrid as illustrated in Fig. 5(b).

We implemented in AWR Microwave Office [8] the SRR analytical model [2], and simulated these two reflection mechanisms to determine their impact on amplitude imbalance, phase imbalance and SRR. We simulated a 4K image noise termination with return loss = 35 dB. We also simulated two cases of mixer reflection coefficients: -3 dB and -9 dB.

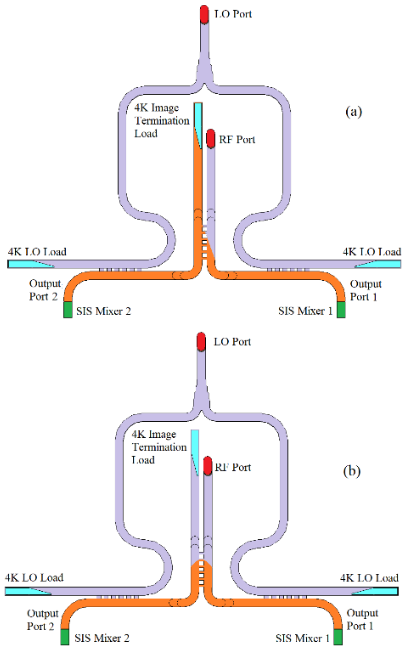

Fig. 5: Schematic illustration of the two reflection paths shown in orange color in the RF waveguide structure: (a) shows the reflections between the mixer ports and the 4K image termination and (b) corresponds to the reflections between the mixer ports due to reverse coupling through the branch-guide coupler.

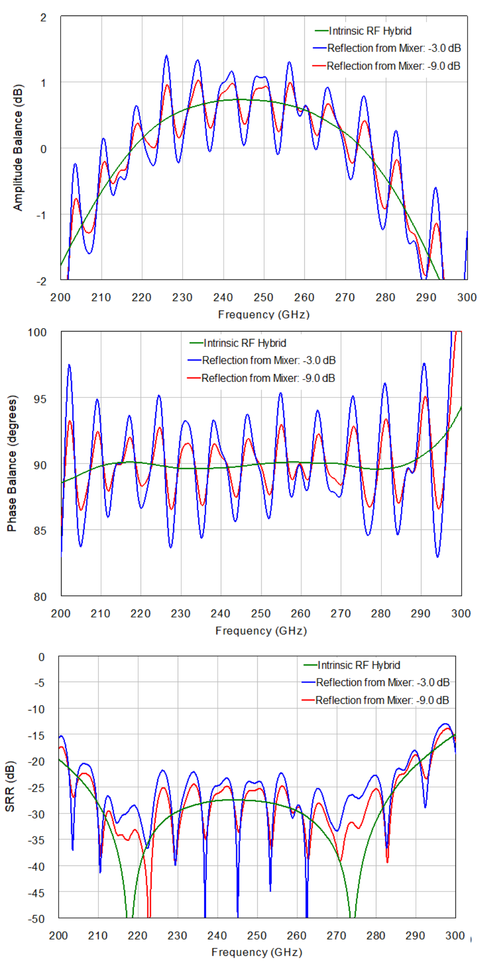

Fig. 6: The effects of reflections from the SIS mixer ports and the 4K image termination on the amplitude balance, phase balance, and sideband rejection ratio.

Fig. 6 shows results of these simulations where we superimpose the characteristics of the intrinsic 2SB module assembly with no reflections from the 4K image and output ports. Results show that amplitude imbalance can degrade by about 1.0 dB and phase balance can degrade by up to 10 degrees. It is seen that with these degradations in phase and amplitude imbalance, the sideband rejection ratio remains ≥ 20 dB which would meet the ALMA Band 6v2 specifications.

III. Measurement of RF Hybrid Test Modules

We fabricated a test module incorporating the quadrature RF hybrid waveguide structure identical to that of the 2SB module, but with WR-3.7 waveguide access ports for measurement with a VNA and WR-3.4 (0.017" x 0.034") 200-300 GHz millimeter wave extenders from Virginia Diodes Inc. [9]. The RF hybrid test module as well as the 2SB mixer module were machined from C360 brass at NRAO Central Development Laboratory with a Matsuura LX-160 5-Axis NC Mill and plated with 1.5 µm of gold [10]. The RF hybrid test module is shown in Fig. 7, and was tested on the VNA system shown in Fig. 8. The effects of the abrupt but small discontinuities at the interfaces between the WR-3.4 waveguides of the VNA extender and the WR-3.7 waveguides of the RF hybrid had negligible impact on results.

Fig. 7: Photograph showing a test RF hybrid module.

Fig. 8: Photograph showing RF hybrid modules under test using Keysight PNA-X 5245B network analyzer with VDI WR-3.4 200-300 GHz millimeter wave extenders.

The simulated and measured amplitude and phase balance are shown in Fig. 9. The simulated and measured SRR are shown in Fig. 10, while simulated and measured RF hybrid characteristics including coupler amplitudes, return losses and sideband rejection ratios are shown in Fig. 11. In all cases, measured results agree well with simulations.

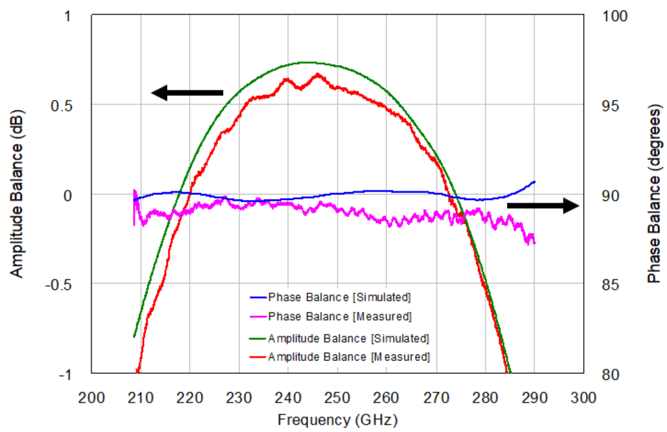

Fig. 9: Simulated and measured amplitude and phase balance of the test RF hybrid.

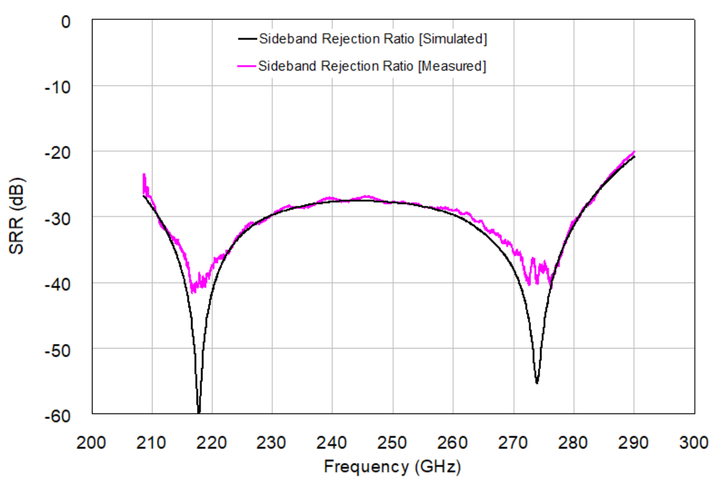

Fig. 10: Simulated and measured sideband rejection ratio of the test RF hybrid. The SRR of the 2 SB assembly was calculated from simulated and measured RF hybrid data and using the analytical model described in [2].

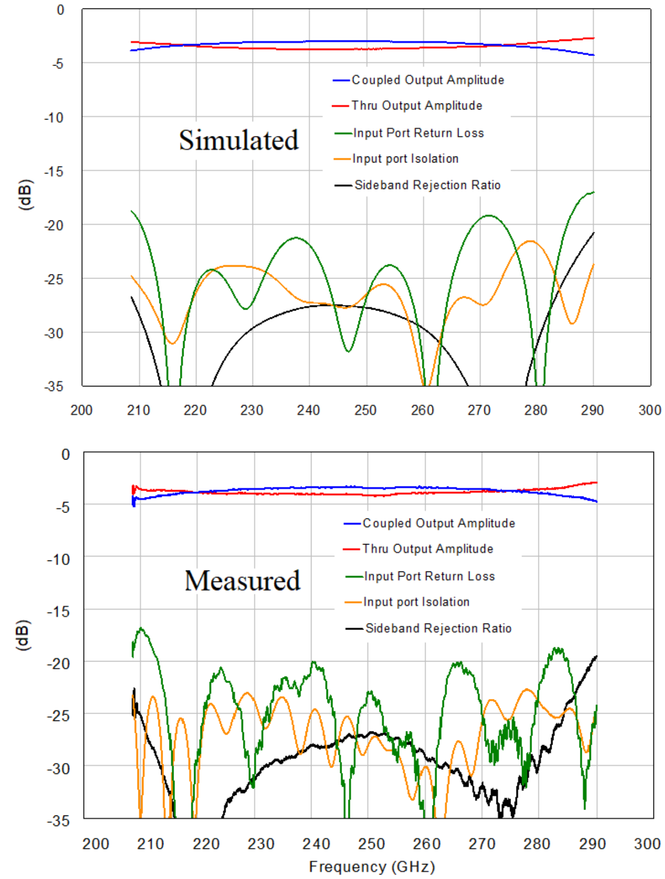

Fig. 11: Simulated and measured RF hybrid characteristics. They include output amplitudes of the thru (red color) and coupled (blue color) ports, input return loss (green color), isolation (Orange color), and sideband rejection ratio (black color).

IV. CONCLUSIONS

The waveguide assembly of the prototype sideband separating SIS mixer for the ALMA Band 6v2 receiver is analyzed to determine its contribution to the sideband rejection. It is shown that the design meets the new receiver specifications.

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