ALMA Memo 316
20 September 2000

Design of a Sideband-Separating Balanced SIS Mixer Based on Waveguide Hybrids

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Abstract

We describe a design for a sideband-separating balanced mixer using four planar single-ended mixer chips connected to the feed horn and LO source by a network of quadrature waveguide hybrids and an in-phase waveguide power divider. The mixer has separate IF output ports for the downconverted signals from the upper and lower RF sidebands, and requires ~14 dB less LO power than a single-ended mixer using a 20-dB LO coupler. The design of the mixer is suitable for scaling to ~700 GHz and can be fabricated using CNC machining techniques.

1. Introduction

Most millimeter and sub-millimeter wavelength receivers in radio astronomy use simple double-sideband mixers to downconvert the RF signal to the intermediate frequency. While such DSB operation is advantageous in continuum observations where the signals received in both sidebands are equally useful, in most spectral line observations the presence of down-converted signals from the unwanted (image) sideband degrades the overall measurement sensitivity. In particular, atmospheric noise in the image sideband can increase the system noise temperature substantially. Some millimeter wave observatories use a mechanically tunable interferometer as a LO diplexer and image filter, but this is only beneficial if the temperature of the image termination is much lower than that of the atmosphere, which can be hard to achieve in practice. Furthermore, interferometric diplexers have a limited instantaneous bandwidth.

The ALMA project will require large numbers of high frequency receivers, each of which must exhibit the best possible performance and be reliable and cost-effective. To respond to these demands we have developed a sideband-separating balanced mixer design which:

- Separates the two sidebands without the use of an interferometer.
- Provides a good 4 K image termination inside the mixer.
- Makes efficient use of local oscillator power.
- Suppresses local oscillator noise.
- Contains no moving parts.

The concepts of sideband-separating and balanced mixers have been known and widely used at RF and microwave frequencies for many years [1]. Single-chip (MMIC) balanced and sideband-separating mixers for 200-270 GHz have been developed at NRAO [2-4] and a single-chip balanced sideband-separating mixer is currently under development. While the work described in this memo is conceptually similar to this earlier work, it explores the advantages of a balanced sideband-separating mixer based on discrete single-ended mixers and conventional waveguide circuitry. This approach may be preferable to the MMIC approach, particularly at the longer millimeter wavelengths, where the large size of single-chip balanced sideband-separating mixers will permit very few mixers per wafer, and at the shorter wavelengths at which loss in the superconducting transmission lines of the MMIC may degrade its performance.

In this memo, we describe a sideband-separating balanced mixer in which the required circuits for combining and phasing the signal and LO power are realized in rectangular waveguide, and the individual mixer elements are identical to those used in single-ended waveguide mixers. By using balanced mixers, each composed of a pair of single-ended mixers, the LO power required by the whole balanced sideband-separating mixer is four times that required to drive a single mixer element, but this is ~ 14 dB lower than that required to drive a single ended mixer using a 20 dB LO coupler. The efficient use of LO power is especially important for the ALMA project because of the difficulty of generating sufficient LO power over the wide receiver frequency bands. The prototype mixer described here has been designed to cover the ALMA band six (211-275 GHz). If tests prove encouraging, a scaled version will be manufactured to investigate the performance in band nine (602-660 GHz).

2. Concept

2.1 Sideband-Separating Mixer

Sideband separation can be achieved using the circuit shown in Fig. 1. Here, the RF signal is divided with a 90-degree phase difference between the two mixers, while the LO power is coupled in-phase to the mixers. The IF outputs are combined in an IF quadrature hybrid at whose output ports the downconverted upper- and lower-sideband signals appear separately. As indicated in the diagram, it is possible to interchange the signal and LO. The

200-270 GHz single-chip sideband-separating mixer described in [4] is similar to Fig. 1, with the LO injected into each mixer through a 17 dB coupler.

It is essential to provide a matched cold load on the fourth port of the quadrature RF input hybrid as USB (LSB) noise from this load is downconverted and appears at the LSB (USB) port of the IF quadrature hybrid. If the RF and LO inputs are interchanged, as indicated in parentheses in Fig. 1, the load on the in-phase power divider becomes the image source. The load on the fourth port of the LO power divider (the in-phase divider in Fig. 1, or the quadrature hybrid if the RF and LO ports are interchanged) contributes thermal noise in both sidebands, which enters the mixers with the LO power. The degree to which this noise contributes to the IF output noise of the mixer depends on how the LO is coupled into the mixer. If balanced mixers are used, as in this report, noise from the termination on the LO divider is diminished by the LO rejection ratio of the balanced mixer.

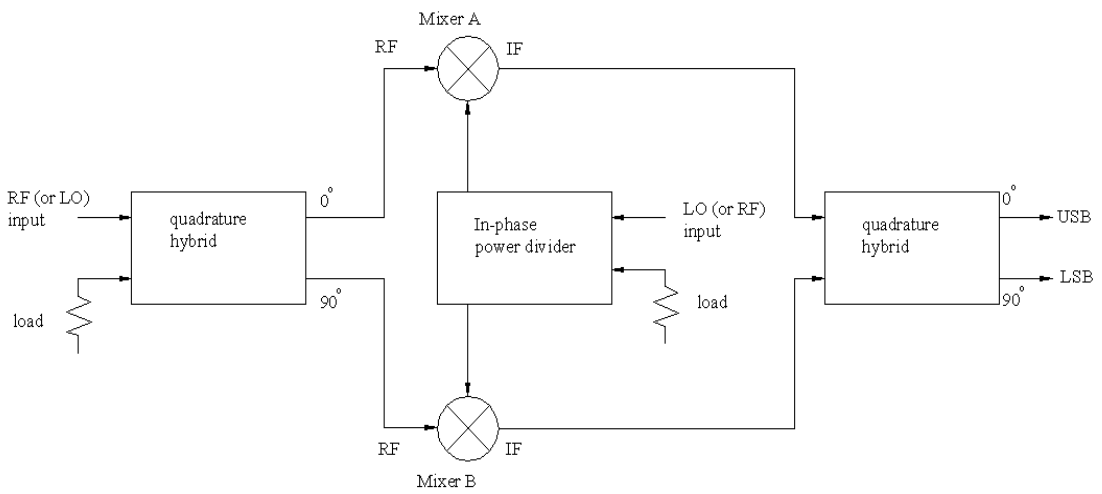


Fig. 1. Sideband-separating mixer.

Amplitude and phase imbalance in the RF and IF quadrature hybrids will reduce the sideband separation ratio of a sideband-separating mixer, as indicated in Fig. 2. Note the surprisingly high degree of imbalance which can be tolerated for a given rejection ratio.

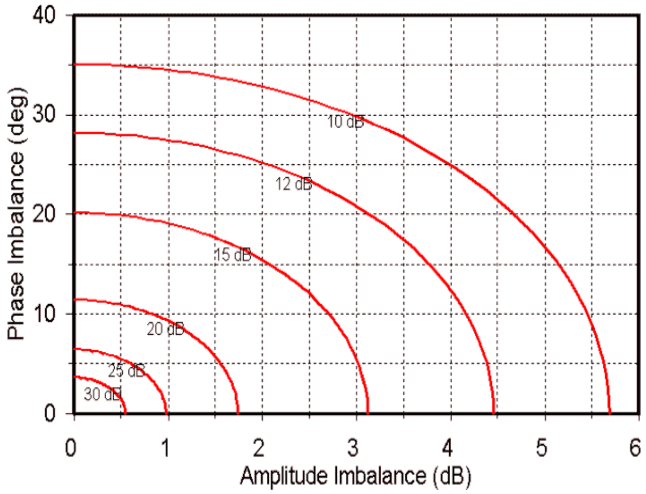


Fig. 2. Effect of amplitude and phase imbalance in sideband-separating and balanced mixers. Contours of constant sideband ratio or LO noise rejection are plotted against amplitude imbalance and phase imbalance.

2.2 Balanced Mixer

A balanced mixer can be constructed from two single-ended mixers and a quadrature hybrid, as shown in Fig. 3. In the general case, the IF outputs can be combined in a 180-degree hybrid (magic-T) at whose difference and sum ports the downconverted signal and LO sideband noise appear separately. When conventional (e.g., Schottky) diodes are used, and they are mounted in the two mixers with opposite polarity, the downconverted signal at the IF ports of the two mixers is in phase, and it is possible to omit the IF hybrid and simply connect the two IF outputs in parallel. With SIS mixers, the anti-symmetric I(V) curve allows the same result to be achieved simply by biasing the two mixers with opposite polarity [2]. In either case (Schottky or SIS) a balanced mixer without an IF hybrid differs in two ways from a balanced mixer with an IF hybrid: (i) the downconverted LO noise now sees a virtual short-circuit at the IF junction point, and (ii) the IF load impedance seen by each mixer is now twice that of the actual IF load. (The 225-300 GHz single-chip balanced mixer described in [2] differed in configuration from Fig. 3 in that it had an IF hybrid.)

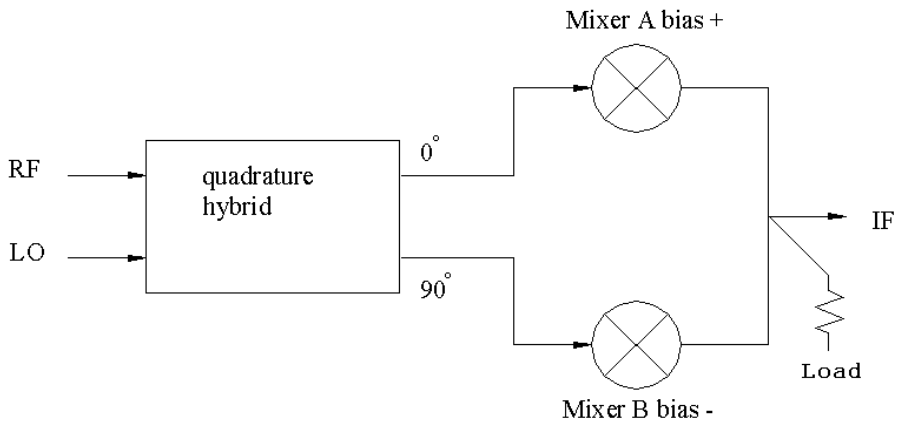


Fig. 3. A balanced mixer with a quadrature RF hybrid and an in-phase IF hybrid.

Amplitude and phase imbalance in the RF and IF hybrids reduce the LO noise rejection of a balanced mixer to the same degree that they degrade the sideband rejection of a sideband-separating mixer. Hence Fig. 2 can be used in both cases. Note the surprisingly high degree of imbalance which can be tolerated for a given LO rejection.

2.3 Sideband-separating Balanced Mixer

Incorporating the balanced mixer of Fig. 3 in the sideband-separating mixer of Fig. 1 gives the sideband-separating balanced mixer shown in Fig. 4. The mixer delivers the downconverted USB and LSB signals to separate IF ports and rejects sideband noise from the LO. It requires 14 dB less LO power than a single-ended mixer using a 20 dB LO coupler.

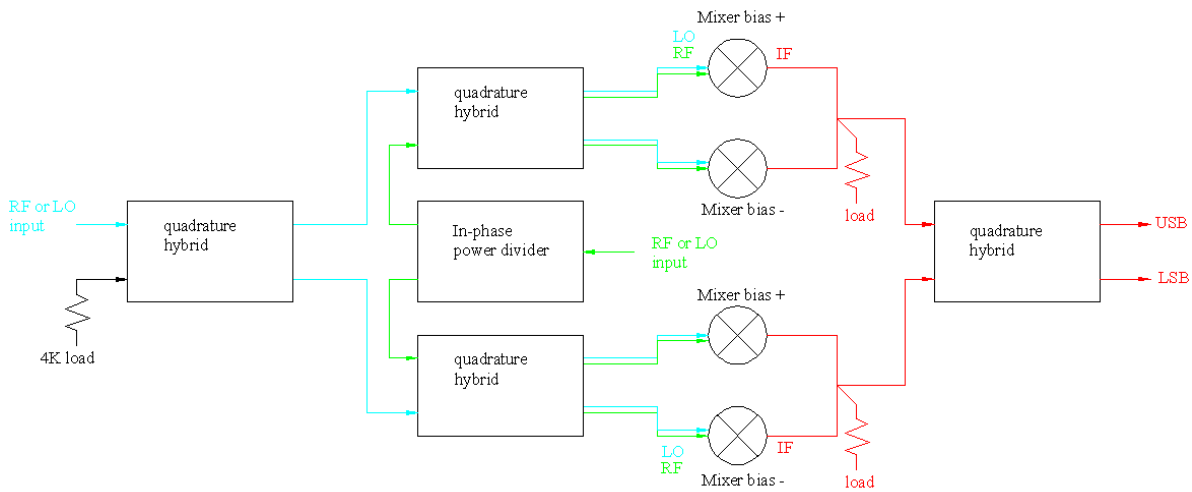


Fig. 4. Schematic diagram of the sideband-separating balanced mixer

3 Design

3.1 Waveguide Quadrature Hybrid

Separating a microwave signal into two equal parts with a 90-degree phase difference is commonly achieved using a quadrature hybrid coupler. Wide bandwidth is possible with two types of waveguide coupler: those in which the two main waveguides have a common thin metal wall (usually the broad wall) containing coupling apertures, and those in which the two main waveguides are interconnected by multiple branch waveguides approximately $\lambda_g/4$ long, usually between the broad walls. Designing a waveguide hybrid coupler for high frequencies involves a number of compromises driven by manufacturing concerns. We have chosen to use the branch-line coupler because of its compatibility with the split-block type of construction and its simplicity of fabrication. The classic equal ripple Chebyschev design applied to a branch-line coupler is difficult to build as the heights of the branch guides are rather small and the height of the main guides varies from section to section of the coupler. To simplify the design and fabrication of hybrids for submillimetre wavelengths, we have kept the main guides at the full height (b = a/2), and made all the branch lines the same height and of equal length and spacing. To avoid the need to machine very narrow slots (*i.e.*, waveguides of small height) we have used relatively wide slots, and fewer than required by a Chebyschev design. In our design, the number of slots and their dimensions are a result of modeling using the QuickWave and Micro-Stripes electromagnetic simulators [5, 6]. We have tried to optimize the bandwidth, coupling, return loss, and isolation while retaining ease of manufacture. The design was verified using a scale model. The CAD results, coupler dimensions and photographs of the machined coupler are shown in figures 5-8.

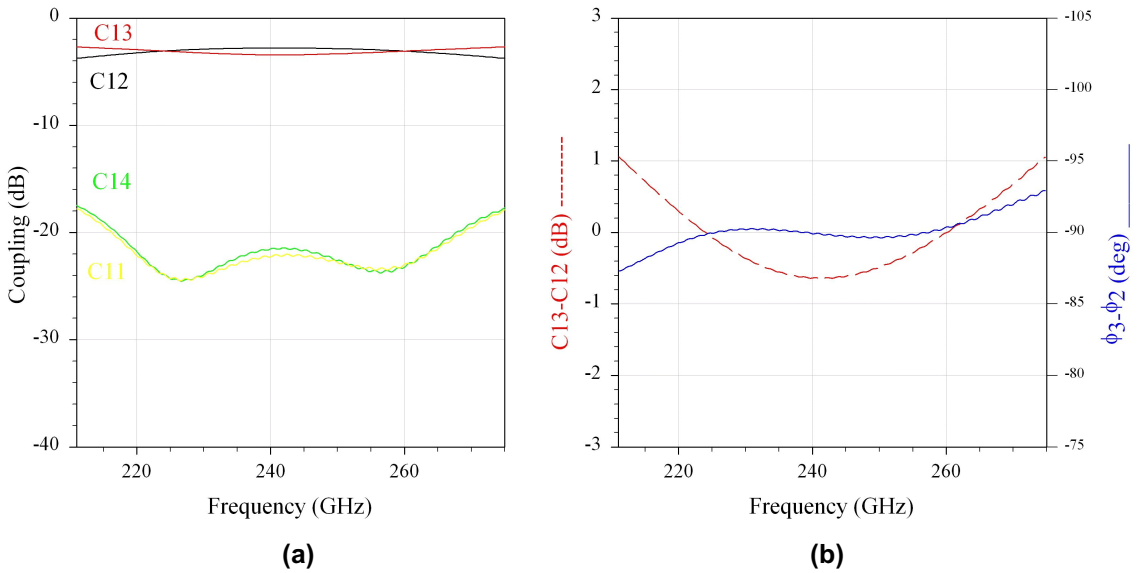


Fig. 5. Simulated performance of the waveguide quadrature hybrid showing (a) the input return loss (C11), isolation (C14), and coupling to the main and side waveguides (C12 and C13, respectively), and (b) the amplitude and phase imbalance, as functions of frequency.

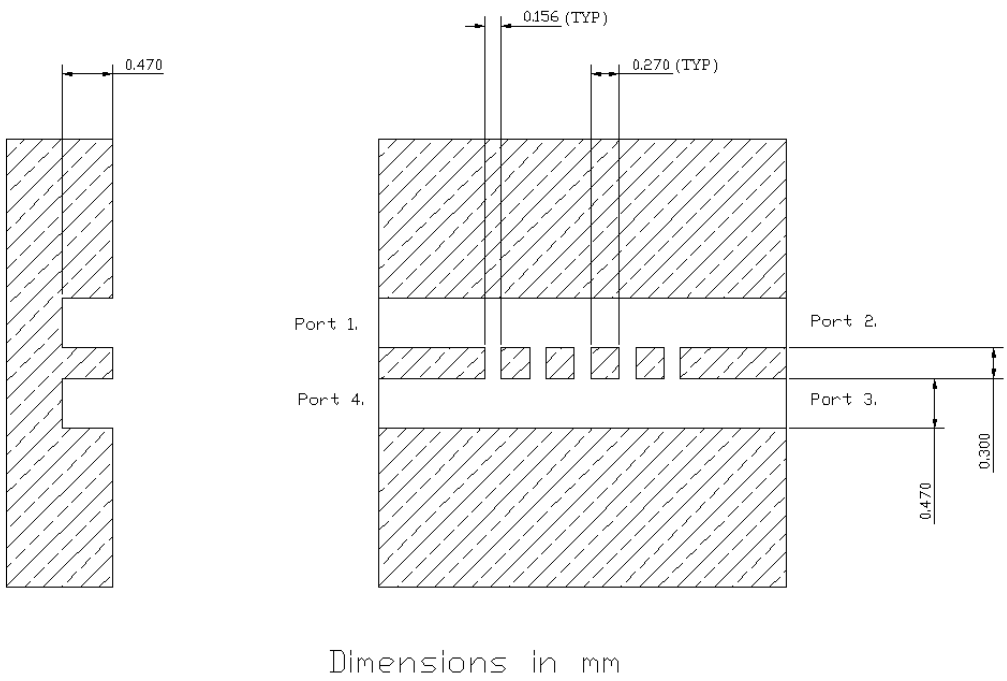


Fig. 6. Diagram of the waveguide branch line quadrature coupler.

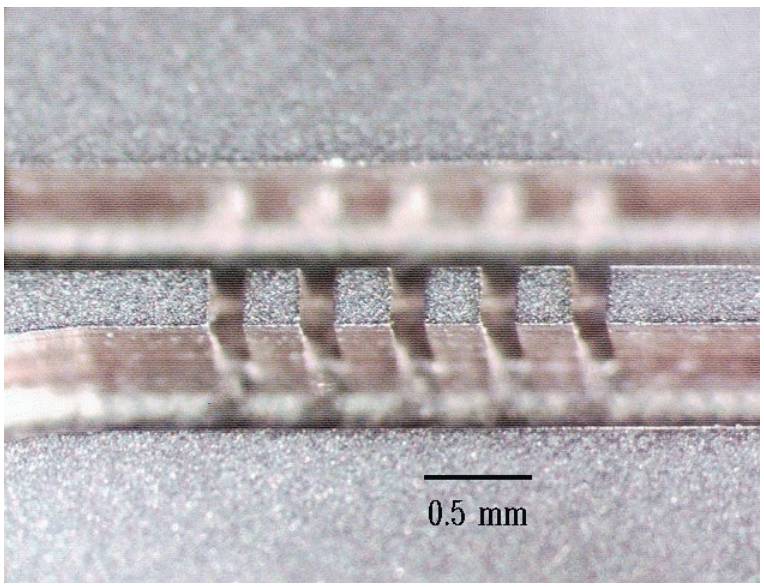


Fig. 7. One side of the split block quadrature hybrid for 211-275 GHz.

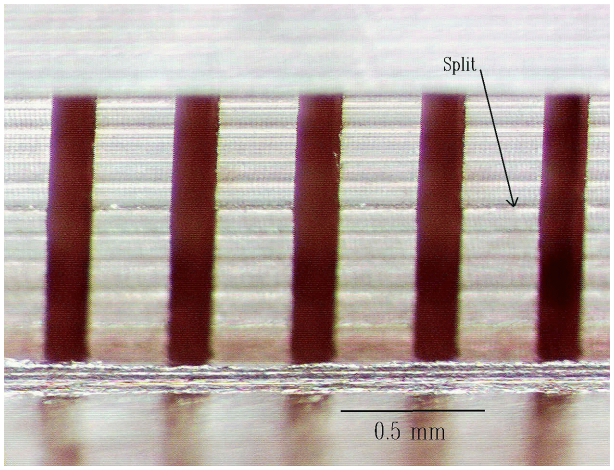


Fig. 8. Assembled split block quadrature hybrid, with part of the block machined away to reveal the internal alignment of the coupler.

3.2 In-Phase Waveguide Power Divider

The in-phase power divider as shown in Fig. 4 can be a broadband waveguide hybrid-T (magic-T) with the fourth port terminated in a load [7]. However, in the present application using balanced mixers, there is no need for the special characteristics of a four-port hybrid junction, and a much simpler waveguide E-plane Y-junction can be used. We have used the MicroStripes EM simulator [5] to design a Y-junction, shown in Fig. 9, which is well matched at its input across the waveguide band. The input match is shown in Fig. 10. If the Y-junction is excited in-phase at its output ports, there is no reflection and the incident power is all delivered to the (matched) input port. If the excitation is out-of-phase, the Y-junction reflects all the incident power. The implications of this in the case of the balanced sideband-separating mixer are as follows: (a) If LO power is reflected from the balanced mixers back into the Y-junction, the reflections from the two balanced mixers will be in phase (by symmetry) and will be delivered to the LO source. If the LO source is mismatched, an additional reflected component will affect the amplitude and phase of the incident LO power, but this should have negligible effect on the overall mixer performance. Note that in the case of ideal quadrature hybrids in the balanced mixers, and identical mixer chips, LO power reflected at the elemental mixers (chips) is all delivered to the RF quadrature hybrid and thence to the 4K load and the feed horn, so no LO power is reflected back into the LO circuit. (b) USB and LSB signal power reflected from the elemental mixers is delivered via the quadrature hybrids to the LO power divider. This reflected signal power has (ideally) a 90 degree phase difference at the ports of the divider, so part of the power will be absorbed in the LO source and part will be reflected back to the balanced mixers. Because the mixers are balanced, signals accompanying the LO do not contribute to the IF output. (If Wilkinson IF power combiners are used in each balanced mixer, as in the present work, these downconverted signals are delivered to the internal terminations of the Wilkinson dividers.)

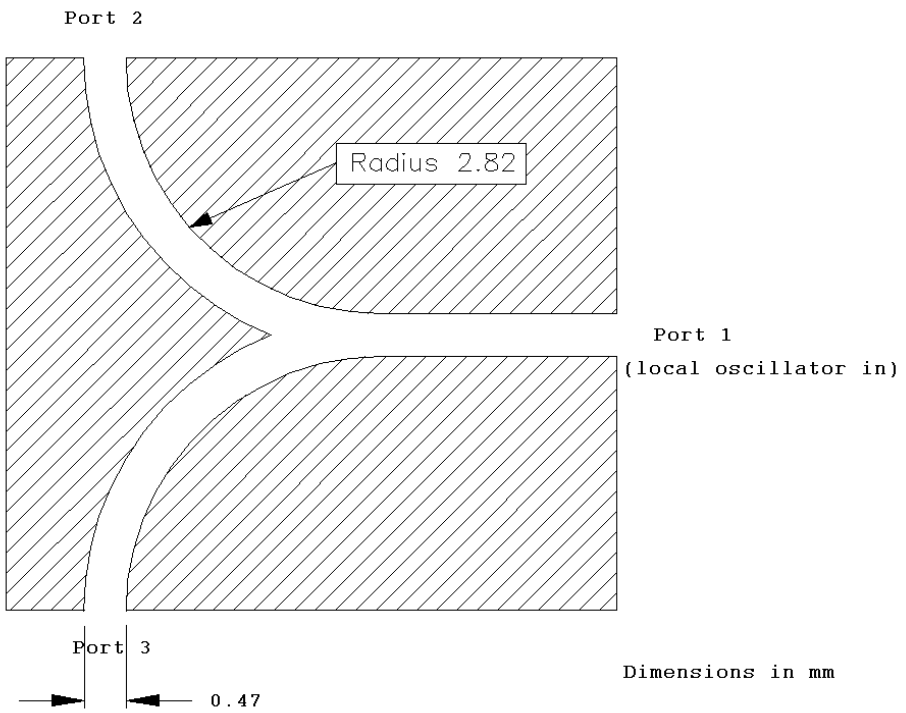


Fig. 9. Diagram of the broadband, matched waveguide Y-junction.

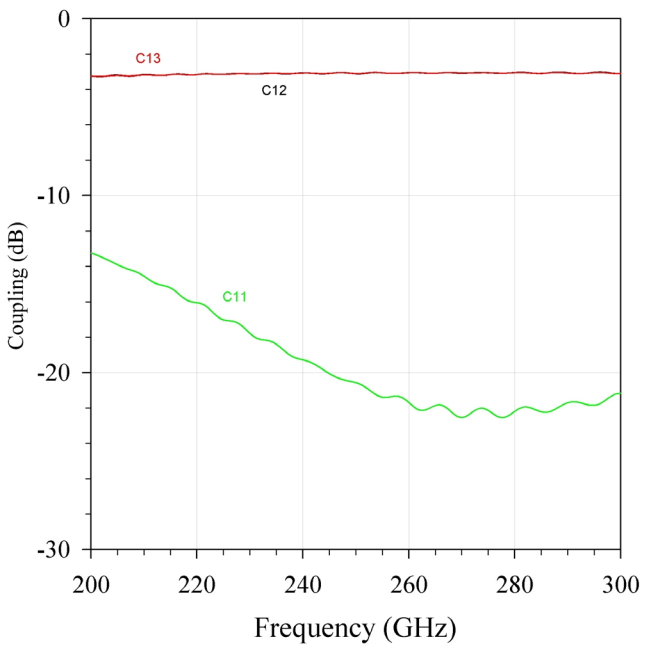


Fig. 10. Simulated performance of the Y-junction showing the coupling to ports 2 and 3 and the input return loss (C11)

3.3 Signal and LO Waveguide Block

The split-block waveguide coupler assembly for the balanced sideband-separating mixer is illustrated in Fig. 11. It contains the three RF quadrature hybrids, LO power divider, and cold image termination, as in Fig. 4. The four mixer chips are mounted in two mating blocks across the waveguides at the top and bottom of the diagram. The split block assembly is made on a CNC milling machine. The main waveguides are made with an end-mill and the coupling slots are formed with a shaving tool with the spindle of the machine locked. A photograph of the two halves of the 211-275 GHz waveguide block is shown in Fig. 12.

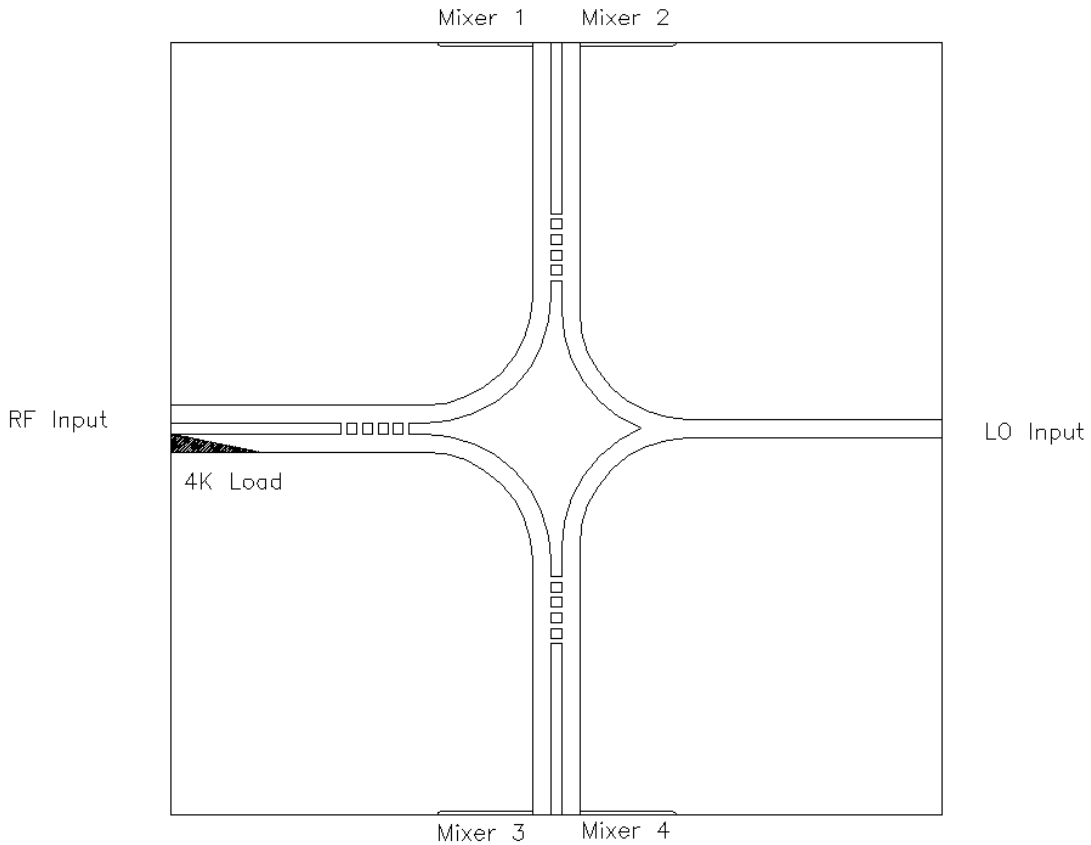


Fig. 11. Configuration of quadrature and in-phase couplers suitable for split block construction.

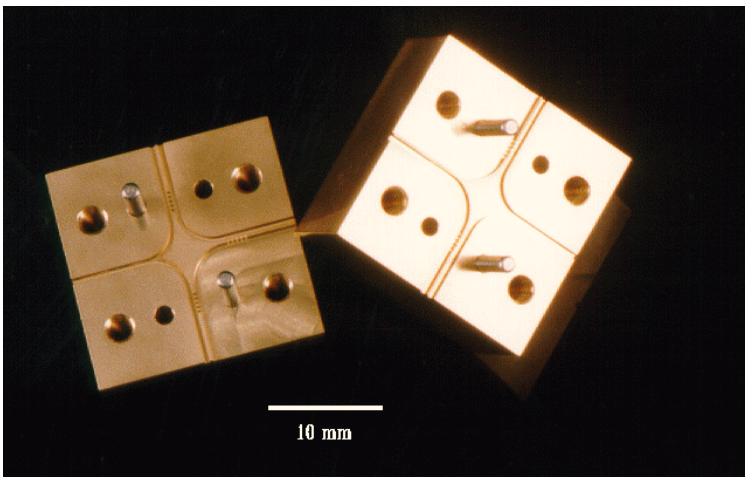


Fig. 12. The two halves of the split-block for 210-270 GHz, showing the three quadrature hybrids and the in-phase Y-junction power splitter.

3.4 IF Quadrature Hybrid

The IF signals from the balanced mixers are combined in a quadrature hybrid that is an integral part of the mixer. For the prototype we chose an intermediate frequency of 3.5-4.5 GHz as existing test equipment at the HIA covers this range. (For ALMA mixers this will be extended). We used the planar circuit simulator Sonnet *em* [8] to design a 3-branch microstrip coupler, the performance of which is illustrated in Fig. 13.

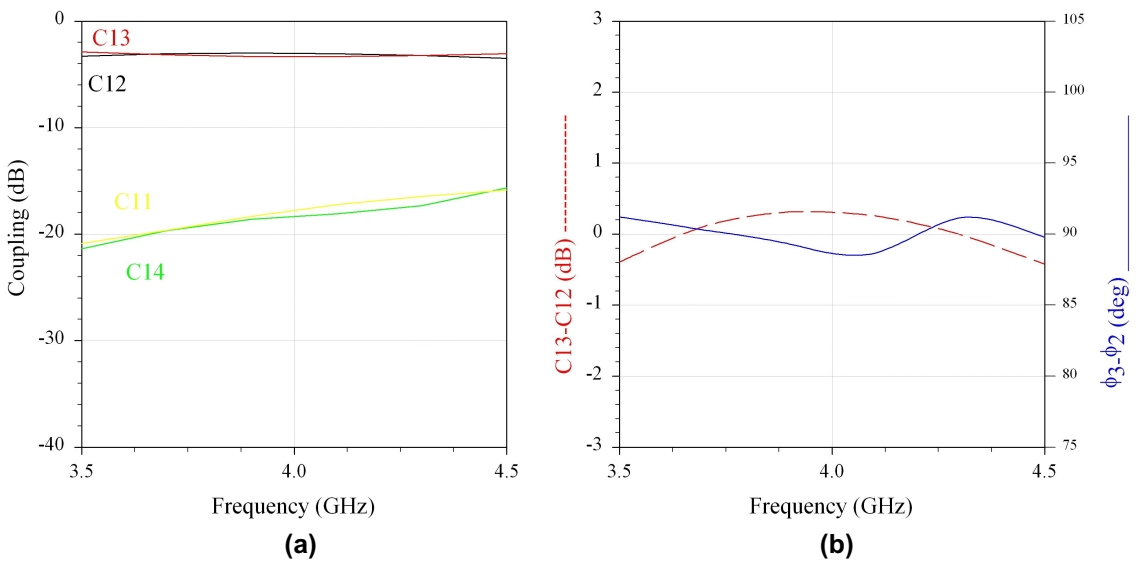
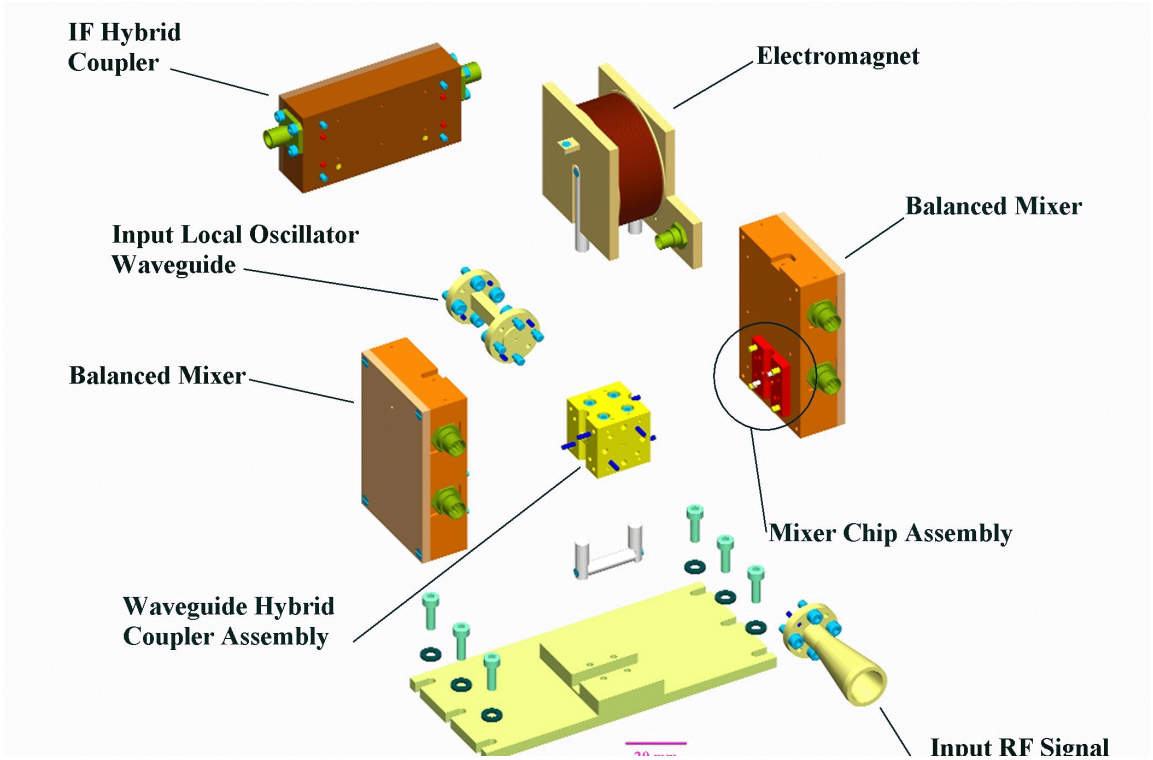


Fig. 13. Simulated performance of the IF coupler, showing (a) the input return loss (C11), isolation (C14), and coupling to the main and side arms (C12 and C13, respectively, and (b) the amplitude and phase imbalance, as functions of frequency.

3.5 Mixer Assembly

An exploded view of the complete 210-270 GHz balanced sideband-separating mixer is shown in Fig. 14. The signal from the telescope is fed into the front of the mixer using a detachable corrugated feed horn. The local oscillator signal is introduced at the rear using over-moded waveguide ending in a taper from WR10 to WR3.7. The central block distributes these signals, appropriately phased, to the balanced mixers on either side. Each mixer uses SIS chips with integrated tuners and hence no mechanical tuning is required.

Within each of the balanced mixers, a simple microstrip Wilkinson power combiner (in-phase hybrid) is used to add the IF output from the two mixer elements. The signals from the two balanced mixers are then recombined in the IF hybrid coupler to allow separation of the sidebands. We have tried to make the mixer easy to assemble and use spring-loaded connectors, allowing easy access to the SIS devices. AC Josephson oscillations in the mixer elements are suppressed by applying a magnetic field using a single bobbin and yoke. The DC bias for each of the four mixer elements is applied independently using integral microstrip bias tees.



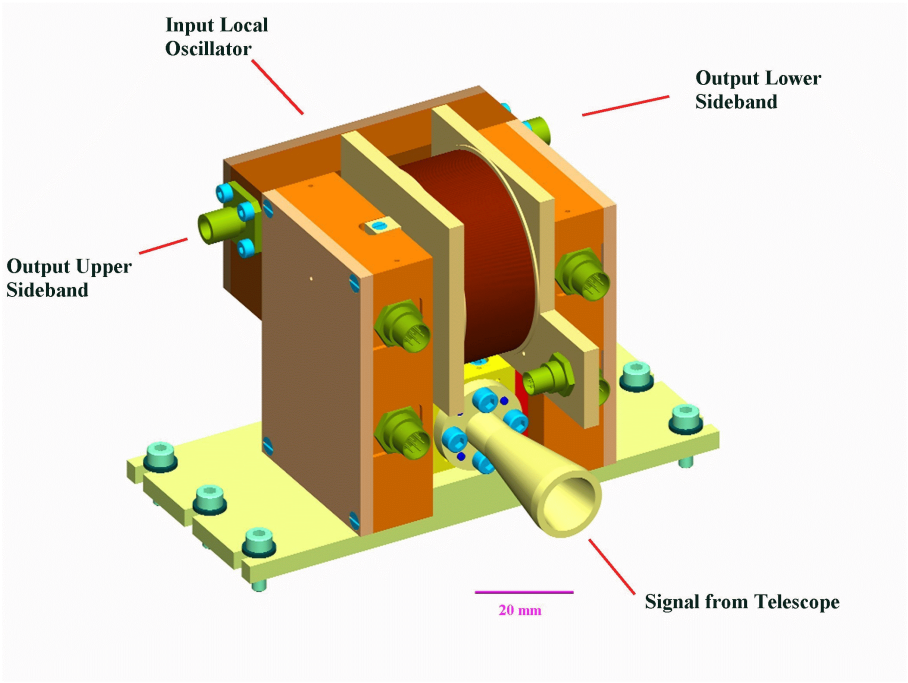


Fig. 15. View of the assembled mixer

The assembled mixer is shown in Fig. 15. A prototype mixer is currently under construction in the NRC precision machine shop and we expect it to be completed in the fall of this year.

Acknowledgments

We wish to thank Jerry Sebesta (NRC) for the drawings of the mixer and Luc Martin (NRC) for the machining of the coupler.

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