ALMA Cycle 8 Study -- Close-Out Report

ALMA Band 6v2 SIS Mixer-Preamp Development

A. R. Kerr, A. Navarrini, P. Mena, P. Dindo, J. Lambert, J. Effland, S. Srikanth, J Mangum
NRAO
A. W. Lichtenberger
UVA/IFAB
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Note: This work was conducted under the dual handicaps of the Covid epidemic and the loss of all the NRAO-CDL mm receiver group's technicians, mostly to retirement and illness. While progress has therefore been less than originally planned, substantial advances have been made, particularly in those areas less dependent on technician support.

Summary

This study continued work towards an ALMA Band 6v2 receiver begun in earlier studies [1][2]. Compared with the current ALMA Band 6 receiver, the proposed Band 6v2 receiver will cover wider RF and IF bands (RF 209-281 GHz, IF 4-16 or 4-20 GHz), have lower noise and flatter gain and noise temperature variation across the IF band, and its beam shape will be cleaner. Progress towards these goals is summarized in seven areas as follows:

1. *Design of an improved SIS mixer with wider RF and IF bands.*
   A new SIS mixer design has been completed in collaboration with IFAB[1]. The new mask set has been received but fabrication of the first wafer of mixers has been delayed by the Covid restrictions and relocation of the IFAB laboratories to a new facility. The first wafer is expected early in 2022.
2. *Development of a DSB mixer chip module to allow measurement of individual SIS mixer chips.*
   Prototype DSB mixer chip modules have been fabricated in the CDL shop. In addition, a 4-K chip test system has been constructed to allow I(V) testing of up to four mixer chip modules.
3. *Investigation of commercial and in-house IF amplifiers, including balanced amplifiers, for direct connection to an SIS mixer.*
   Commercial cryogenic IF amplifiers have been evaluated and shown to have very low noise, but can have substantial gain changes between thermal cycles. IF amplifiers designed in the CDL (under a separate ALMA Study) using Diramics transistors have low noise, but currently only to 16 GHz.
4. *Design of an RF quadrature hybrid for use in sideband-separating (2SB) SIS mixers.*
   A superconducting drop-in beamlead hybrid on a Si membrane (SOI) is being designed in collaboration with UVA-IFAB.
5. *Design of a superconducting IF quadrature hybrid as required to separate the sidebands in a 2SB mixer, and also for use in balanced IF amplifiers.*
   Work is under way on a superconducting 4-20 GHz quadrature hybrid, also in collaboration with UVA-IFAB.
6. *Study of alternative ortho-mode transducer (OMT) designs.*
   Three OMT designs for the expanded Band-6 RF band are under study. One has been completed in the CDL shop and is currently under test. The second design is currently being fabricated in the CDL shop. The third OMT type is in an advanced design stage.
7. *Improvement of the Band-6 feed horn and optics to minimize sidelobes and cross-polarization..*
   Work on an improved feed horn and optical system is under way but has not yet been completed.

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[1]IFAB is Innovations in Fabrication at the University of Virginia, formerly the University of Virginia Microfabrication Laboratory, UVML.

Progress towards an ALMA Band 6v2 receiver

1. Design of an improved SIS mixer with wider RF and IF bands.

This work is a continuation of the work on Band 6v2 SIS mixer chips and chip modules described in our ALMA Cycle-7 Study Project Close-Out Report [2]. A new SIS mixer design has been completed in collaboration with IFAB. The new mask set has been received but fabrication of the mixers has been delayed by Covid restrictions and relocation of the IFAB laboratories to a new facility. The first wafer is expected early in 2022. While the current Band 6 SIS mixers [3] were fabricated on fused quartz and required dicing and lapping to their final size, the Band 6v2 mixers will be fabricated on a 5 µm Si membrane using the IFAB Silicon-On-Insulator (SOI) process which allows beamleads to be used and requires no dicing or lapping. Beamleads will allow easier mounting of the chips in a waveguide block. Fig 1.1 shows the layout of the wafer and details of the individual mixer chips. To account for processing variations there are multiple tunings, and a number of diagnostic circuits are also included.

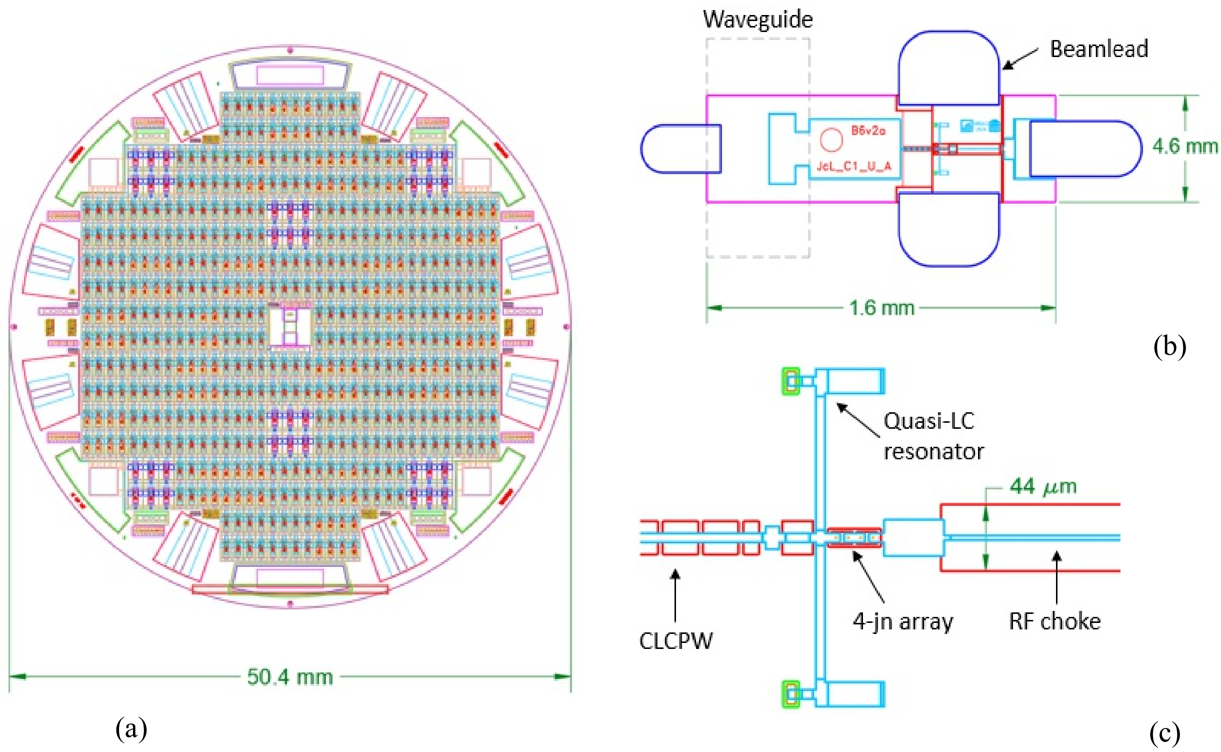
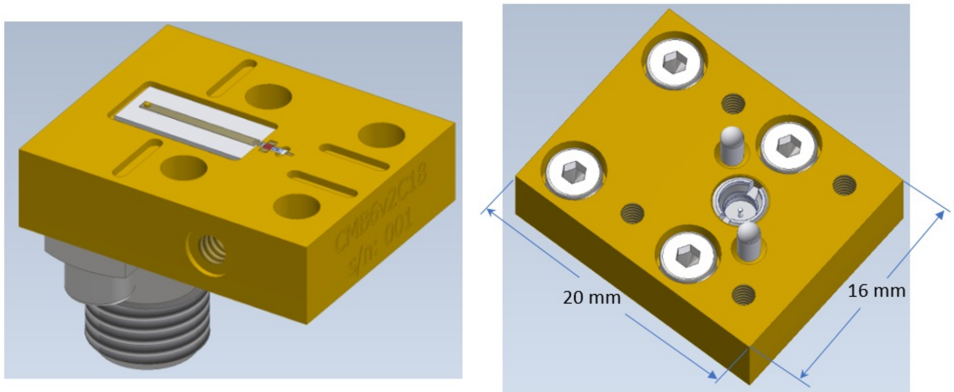


Fig. 1.1 Details of the Band 6v2 SIS mixer wafer and chips. The wafer contains 492 mixer chips with multiple tuning circuits and a number of test circuits. Red: base Nb. Light blue: Nb wiring layer. Dark blue: beam leads. Green: vias between layers. Magenta: outline of Si membrane substrate.

2. Development of a mixer chip module to allow measurement of individual SIS mixer chips.

The current Band 6 sideband-separating SIS mixer [3] contains two mixer chips permanently mounted in the mixer block which also contains the RF quadrature hybrid, image termination, LO coupler, LO terminations, and IF interstage network. The mixer chips can not be tested at 4 K before they are mounted in a sideband-separating mixer block, and it is difficult to remove a bad chip without damaging the mixer block. For the Band 6v2 prototypes it has been decided to use individual chip modules. This allows testing of individual chips at 4 K and selection of well matched pairs of chips for attachment to the main mixer block. Fig. 2.1 shows two prototype chip modules, one with a standard 2.92-mm connector and the other with a SMPM blind-mate connector. The blind-mate connector allows an IF preamplifier to be connected directly to the chip module without an intervening cable or adapter, thus minimizing the electrical distance between mixer and preamp. Also, direct connection should improve reliability because of the reduced component count. At the time of writing, prototype modules have been fabricated in the CDL shop and are ready for mixer chips when they are available. This connectorized modular mixer design allows swapping of the IF chain components for test and verification of different architectures during prototyping stage of the project. The design might be ultimately be modified to an integrated, non-modular version, better suited for subsequent Band 6v2 receiver production.



(a) (b)

Fig. 2.1 Prototype chip modules. (a) With a 2.92-mm connector. (b) Rear view of with the SMPM blind-mate connector.

As liquid helium is no longer available on a regular basis, DC testing of mixer chips at 4 K will be done in a new test system with a closed-cycle refrigerator, designed to have relatively short cool-down and warm-up times. The chip-test Dewar holds up to 4 chip modules and is wired to allow measurement of I(V) characteristics using the CDL standard 6-wire bias circuit. Fig. 2.2 shows the chip test set.

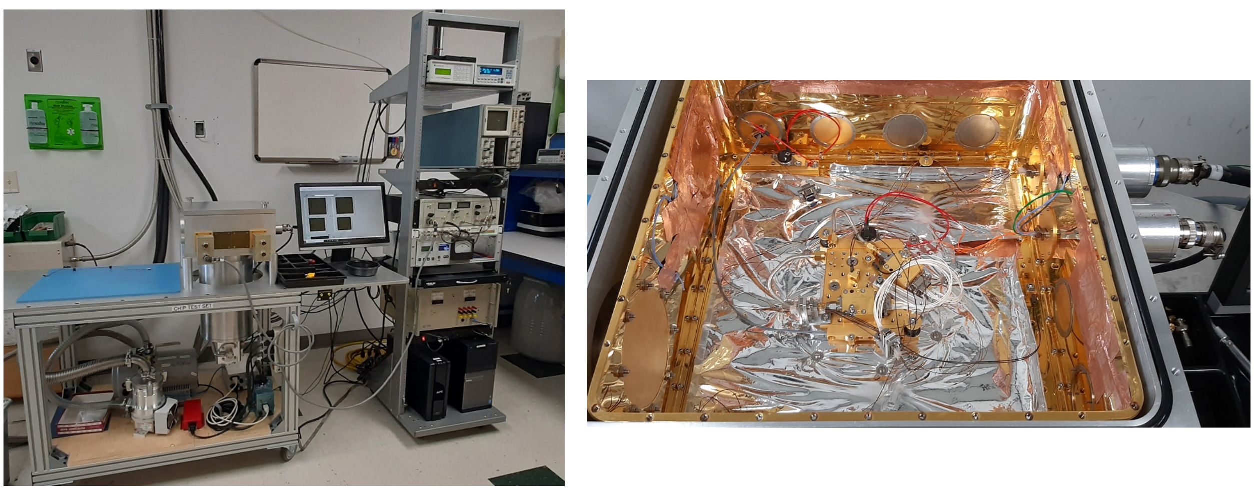


Fig. 2.2 The 4-K chip test for rapid testing of multiple SIS mixer chips mounted in chip modules.

3. Investigation of commercial and in-house IF amplifiers, including balanced amplifiers, for direct connection to an SIS mixer.

Commercial cryogenic IF amplifiers have been investigated and shown to have very low noise and low power dissipation, but they can have substantial gain changes between thermal cycles. This is illustrated in Fig. 3.1.

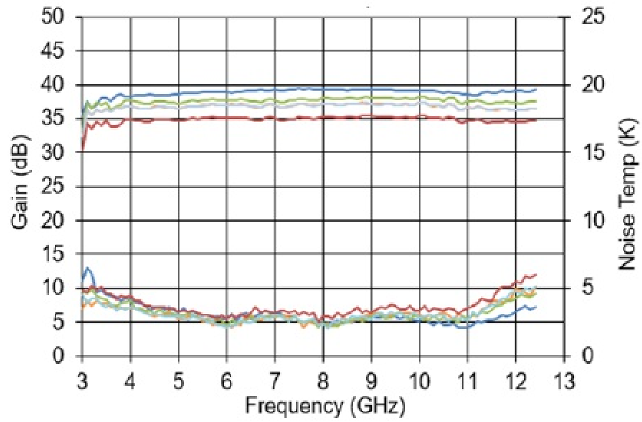


Fig. 3.1. Gain and noise changes for a LNF-LNC4_12NRAOB amplifier on successive cool-downs.

IF amplifiers designed in the CDL (under a separate ALMA Cycle 8 Study), using Diramics transistors, have low noise and flat gain and cover 4 to ~16 GHz. Fig. 3.2 shows the gain and noise temperature of two experimental amplifiers with Diramics transistors and clearly indicates the inevitable tradeoff [4] between noise temperature and bandwidth.

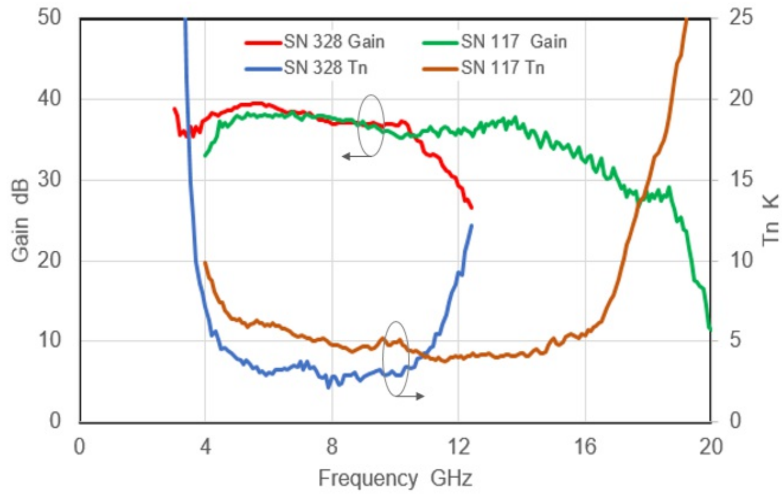


Fig. 3.2. Gain and noise temperature of experimental IF amplifiers using Diramics transistors. Green and brown curves: 4-16 GHz. Red and blue curves: 4-12 GHz.

The strong interaction between an SIS mixer and an IF amplifier connected directly to it with no isolator is the topic of a parallel Cycle 8 study: "Extending IF Bandwidth of Band # 6 SIS Mixer-Preamps to 12 GHz and 16 GHz with Optimal Noise Performance," by M. Pospieszalski, and references [4][5]. It is clear that to achieve flat receiver gain and noise temperature over a wide IF band (4-16 GHz or 4-20 GHz) isolators or balanced amplifiers are needed. Suitable isolators have been developed at Smithsonian Astrophysical Observatory and were evaluated in [2].

Balanced IF amplifiers consist of two single-ended amplifiers in parallel, connected at the inputs and outputs by quadrature hybrid couplers as indicated in Fig. 3.3.

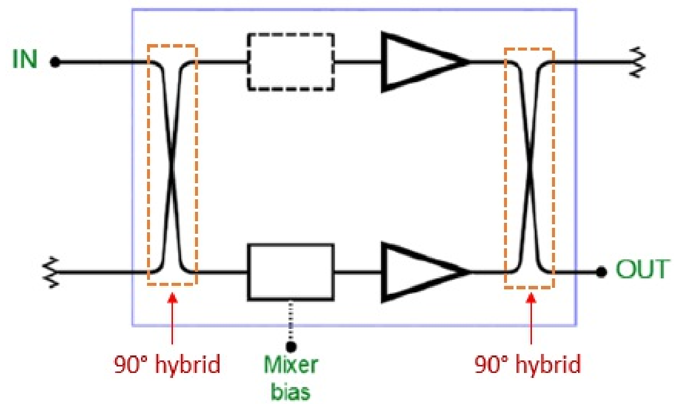


Fig. 3.3. A balanced amplifier consisting of two hybrids, two amplifiers. For use as an IF amplifier with an SIS mixer a mixer bias-T is included in the amplifier circuit. The black dashed box is the dummy bias-T required to maintain the symmetry of the circuit.

In an ALMA Cycle 5 study [1] we developed a cryogencially cooled balanced 4-12 GHz amplifier in collaboration with Low Noise Factory in Sweden. It used supercondcting quasi-lumped-element hybrids fabricated on a 3 x 1 mm quartz chip, small enough to embed within the balanced amplifier housing. With the recent change in goals for a future ALMA correlator and transmission system, the IF band is to be expanded to 4-16 GHz or 4-20 GHz. That requires hybrids to cover the same band, and work is under way on a 4-20 GHz design. Progress on the design of a new superconducting hybrid is described in section 5.

4. Design of an RF quadrature hybrid for use in a sideband-separating (2SB) SIS mixer.

The image rejection of a sideband-separating receiver depends directly on the power and phase balance between the outputs of the RF quadrature hybrid. The output balance of the waveguide branch-line hybrids used in the current ALMA Band 6 mixers is limited by the machining tolerance on the widths of the narrow but deep waveguide branch-lines – 122 µm wide x 470 µm deep. To improve the balance of the RF hybrid in the Band 6v2 mixer a hybrid on a silicon membrane is being developed.

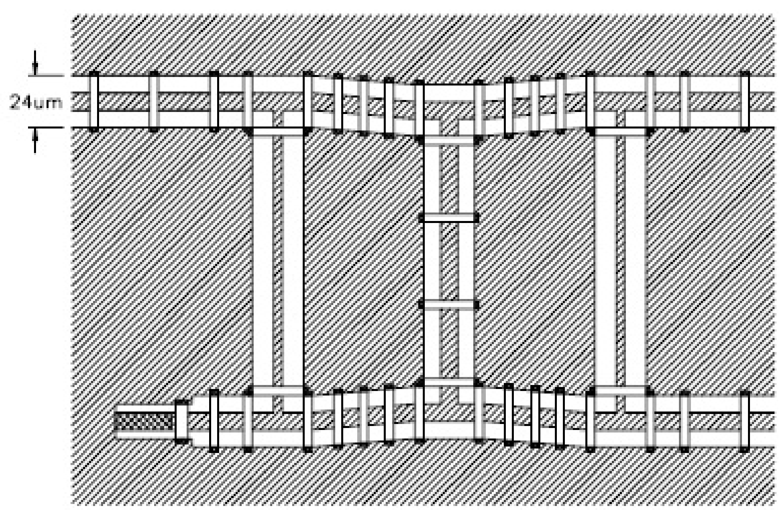


Fig. 4.1. Planar 200-300 GHz branch-line quadrature hybrid and image termination, as used in [6]-[8].

The single-chip balanced and sideband-separating SIS mixers developed in the CDL in 1996-2000 [6]-[8] used a planar superconducting RF quadrature hybrid on a thick fused quartz substrate, as shown in Fig. 4.1. For the Band 6v2 mixer, a similar approach is being used, but on a 5-µm Si membrane (SOI) chip with beamleads. The hybrid will be inserted into a shallow channel in the waveguide block of the mixer body. Figs. 4.2 and 4.3 give details of the Si membrane hybrid. The superconducting hybrid is being designed in collaboration with UVA-IFAB.

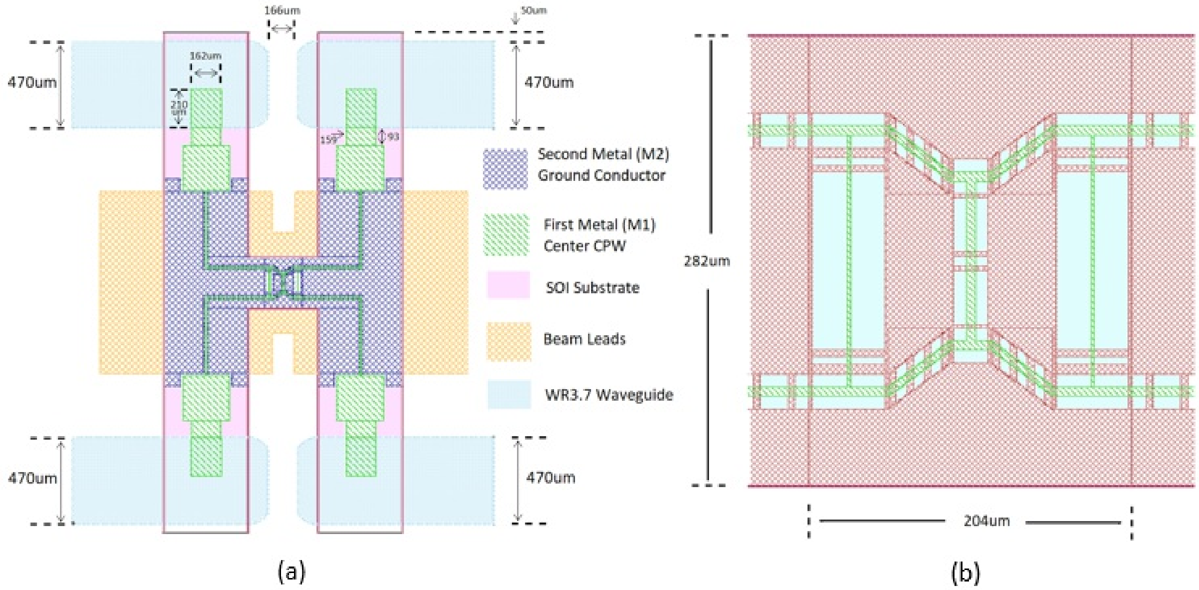


Fig. 4.2. The proposed RF Hybrid on a 5-μm Si membrane. (a) Showing the complete hybrid and the WR-3.7 waveguides. (b) Detail of the branch-line coupler.

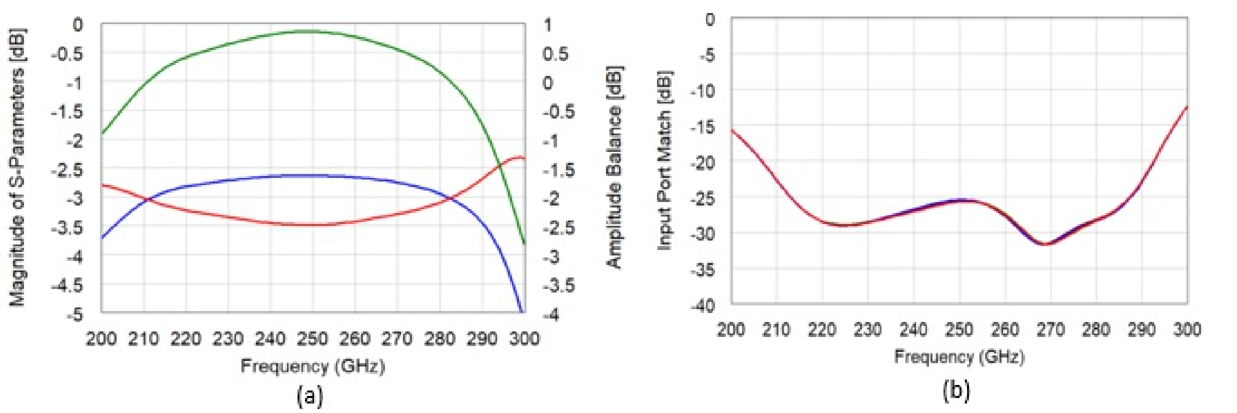


Fig. 4.3. Characteristics of the RF hybrid. (a) Red and blue: output port coupling (left scale). Green: amplitude imbalance (left scale). (b) Input match. The coupled port phase difference is ± 2 deg from 200 to 295 GHz.

5. Design of a superconducting IF quadrature hybrid as required to separate the sidebands in a 2SB mixer, and also for use in balanced IF amplifiers.

The superconducting IF hybrid developed for the 4-12 GHz balanced amplifier in the ALMA Cycle 5 study used quasi-lumped-element coupled transmission lines to emulate a coupler with three quarter-wave sections. The coupled inductors in that design required niobium lines 4 μm wide whose spacing and alignment between layers was critical. To accommodate the wider 4-20 GHz IF band alternative designs have been explored. These included:

(i) Parallel coupled transmission line couplers with a homogeneous dielectric [9]. These require a sandwich of two or three layers without gaps and are not well suited for cryogenic operation.

(ii) Parallel coupled transmission line couplers with an inhomogeneous dielectric. Because the propogation constants are different for the even and odd modes, the design for wide bandwidths is not straight forward.

(iii) Asymmetric multi-section coupled-transmission-line directional couplers [10]. The bandwidth within which the output phase difference is close to 90 deg. is insufficient.

(iv) Multi-section couplers with coupled-line sections of unequal length [11]. The relative orientation of the four ports is not appropriate for the present applications.

Despite its design difficulties, option (ii) appears to be the best choice for a multi-octave cryogenic quadrature hybrid and we are currently taking this approach. It is a modified version of the design described in [12] which uses a Lange coupler as the center section of a three-stage coupler. To eliminate the need for bondwires in the crossover region of the coupler the two Nb conductors are on different layers. And to reduce the difference in even and odd mode propagation constants, a 100-µm layer of Si from a SOI wafer is bonded to the top of the assembly. The current configuration is shown in Fig. 5.1.

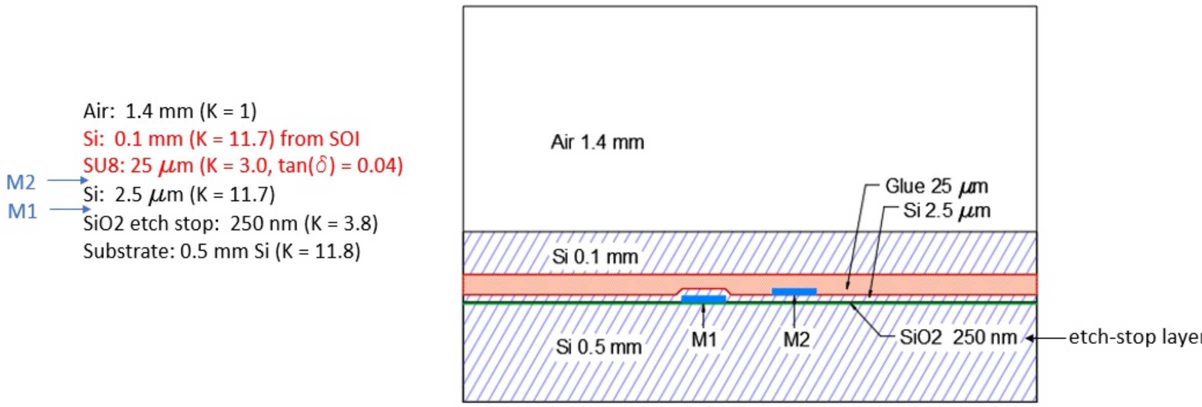
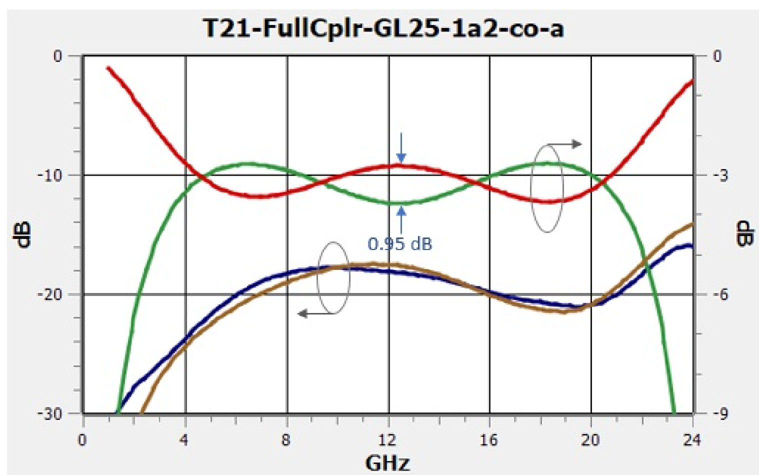


Fig. 5.1. Proposed layer configuration of the superconducting 4-20 GHz quadrature hybrid. Conductors M1 and M2 are Nb.

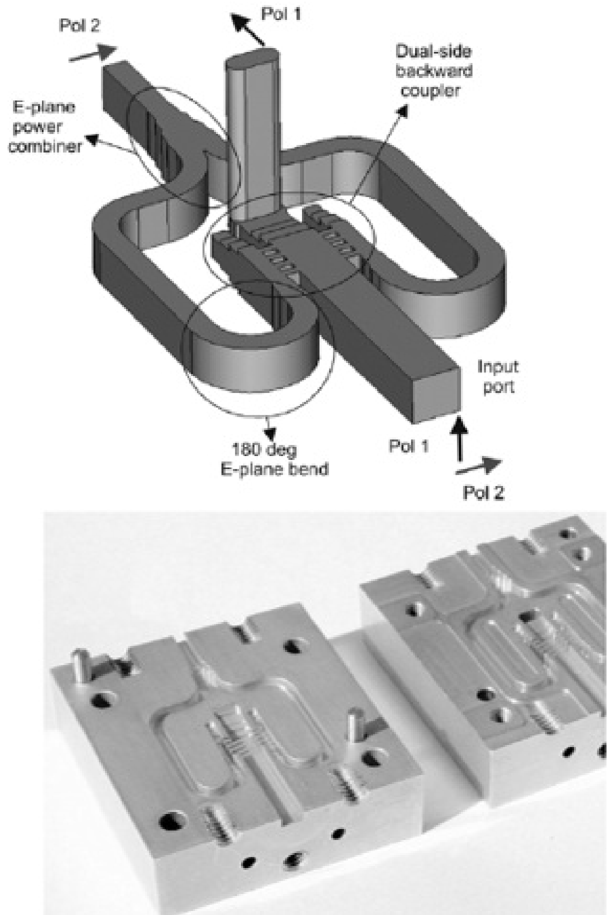
Fig. 5.2. Simulated response of the proposed hybrid. Red, green: coupled outputs. Brown: isolation. Black: input reflection coefficient.



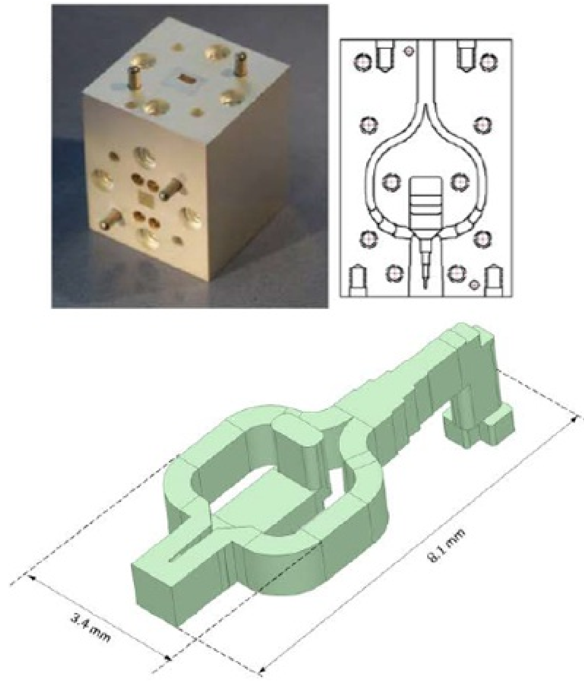
Work on the superconducting IF hybrid is continuing towards a final design for the Band 6v2 receiver.

6. Study of alternative ortho-mode transducer (OMT) designs.

The three OMT designs shown in Fig. 6.1 are under study for the Band 6v2 receiver with its expanded RF band . Prototypes of one have been completed in the CDL shop and are currently under test, and the second design is currently being fabricated. The basic OMT configurations have been modified to allow the SIS mixers to be mounted on opposite faces of the OMT but with the same orientation; this is necessary to accommodate the complete OMT-mixer assembly within the limited space in the ALMA cartridges. The three OMT designs incorporate a quasi-circular waveguide input matched to the circular waveguide output of the feed-horn. Waveguide transitions have been fabricated to allow testing of the OMTs.

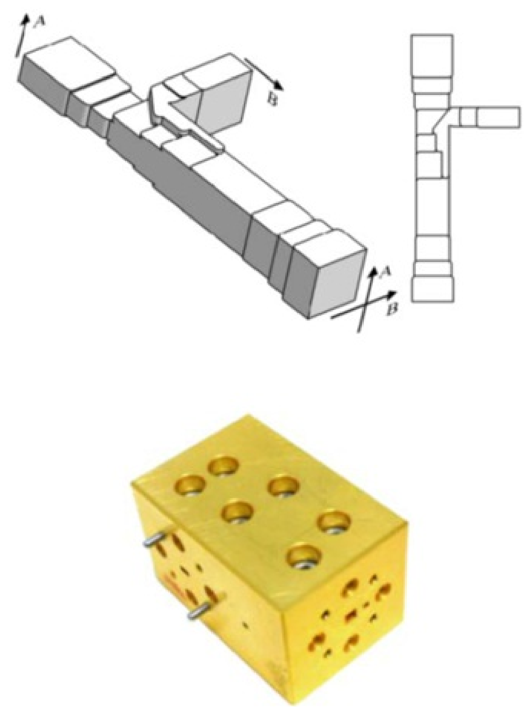


(a) Navarrini & Nesti OMT [13]



(b) Mena/Dunning Type II OMT [14]

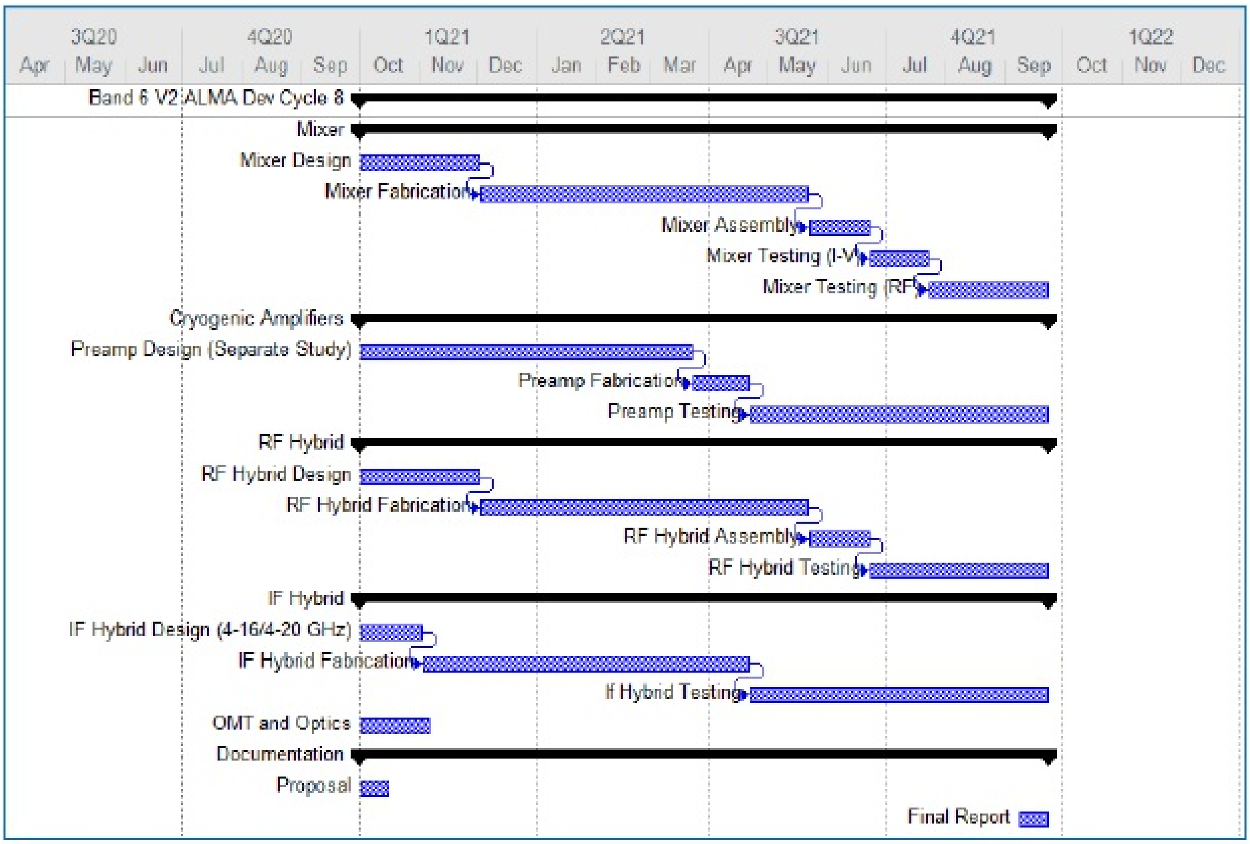
Fig. 6.1. OMTs under evaluation for Band 6v2



(c) Srikanth/Erickson/Dunning Type III OMT [15]

7. Improvement of the Band-6 feed horn and optics to minimize sidelobes and cross-polarization.
A study of the effect of position errors of the 4-K optical components (horn and two mirrors) indicates negligible effect on cross-polarization. The next phase of the study will include the vacuum window and IR filter, and is planned for the next year.

8. Conclusions
The Gantt chart below shows the work schedule submitted with the study proposal. Substantial progress has been made on all items, but was limited by two factors: the loss of all our millimeter wave receiver technicians, and the delays caused by operating under Covid restrictions. The work will be continued under the ALMA Cycle 9 Band 6v2 construction project which is scheduled to begin in the second quarter of 2022.



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