ALMA Cycle-7 Study Project: Close-Out Report

ALMA Band 6v2 SIS Mixer-Preamp Development

A. R. Kerr, J. Lambert, P. Dindo, J. Effland, S. Srikanth, J Mangum
NRAO

A. W. Lichtenberger
UVA

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The goal of this project was to continue the development of an SIS mixer-preamplifier combination for a future ALMA Band 6 receiver upgrade, referred to here as the Band 6v2 upgrade. Band 6v2 would have a wider IF band with flatter noise temperature, and an increased RF bandwidth. A number of options are being explored with the goal of choosing a best design for the upgrade. The options include SIS junctions with aluminum nitride tunnel barriers (Nb/Al-AlN/Nb) instead of the usual aluminum oxide barrier (Nb/Al-AlOx/Nb), ferrite isolators which reduce interaction between the mixer and the amplifier at the expense of noise temperature, balanced IF amplifiers (which require no isolator). This work was done in the period 10/1/2019-4/11/2021.

Our earlier work on a second generation Band-6 receiver was based on the then-planned correlator upgrade (CUP), and a corresponding (but unplanned) upgrade of the telescope electronics and IF transmission system, which together would double the useable IF bandwidth from the current 4 GHz per sideband per polarization to 8 GHz. Following a Conceptual Design Review (CoDR) in September 2018, the ALMA administration changed the goals for receiver upgrades to an IF bandwidth of 12 or 16 GHz per sideband per polarization, and expanded Band 6 by 5 GHz to 211-280 GHz.

SIS junctions with AlOx and AlN tunnel barriers

To achieve a flatter receiver noise temperature over a wider RF band, SIS junctions with a higher critical current density (Jc) are needed. The Nb/Al-AlOx/Nb SIS junctions used for the current Band 6 receivers were made in the UVA Microfabrication Laboratory (UVML) almost 20 years ago. Since then, the fabrication process of Nb/Al-AlOx/Nb tunnel barrier has been improved, resulting in the ability to produce smaller junctions with moderately higher Jc. At the same time, UVML has Developed a process for making Nb/Al-AlN/Nb SIS junctions with much higher current density.

Experimental SIS mixer chips for Band 6v2, based on the improved Nb/Al-AlOx/Nb junctions, and the new Nb/Al-AlN/Nb SIS junctions have been designed, and a mask set acquired. An initial wafer of Band 6v2 mixer chips will be fabricated once the Covid-19 restrictions permit. A typical design is shown in Fig. 1.

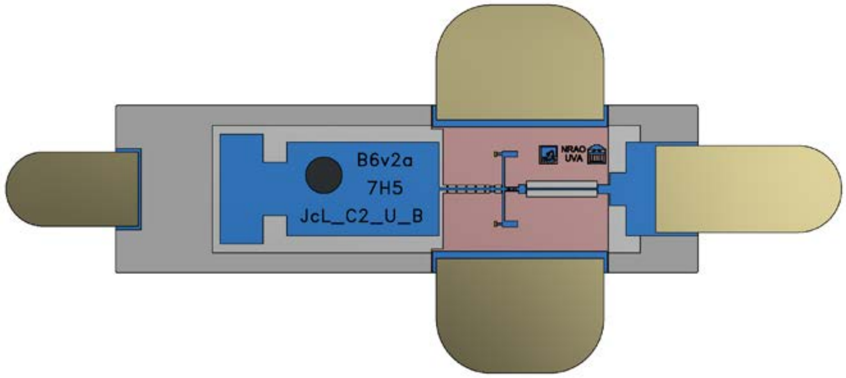

Fig. 1. An SIS mixer chip for Band 6v2. The substrate is a silicon membrane with gold beam leads.

SIS mixer chip modules

Experience with the original Band 6 SIS mixers indicated that mounting two untested mixer chips in a sideband-separating mixer block was inefficient for production on the ALMA scale. After two of these chips were mounted in a sideband-separating mixer block, only about a third of the blocks met ALMA specifications. We plan to improve the Band 6v2 yield to a more acceptable level by mounting the untested chips permanently in individual modules, as shown in Fig. 2. The chip modules can be cooled rapidly to 4 K to test their I(V) characteristics and DSB mixer properties. This will allow selection of pairs of well-matched modules for use in sideband-separating mixers.

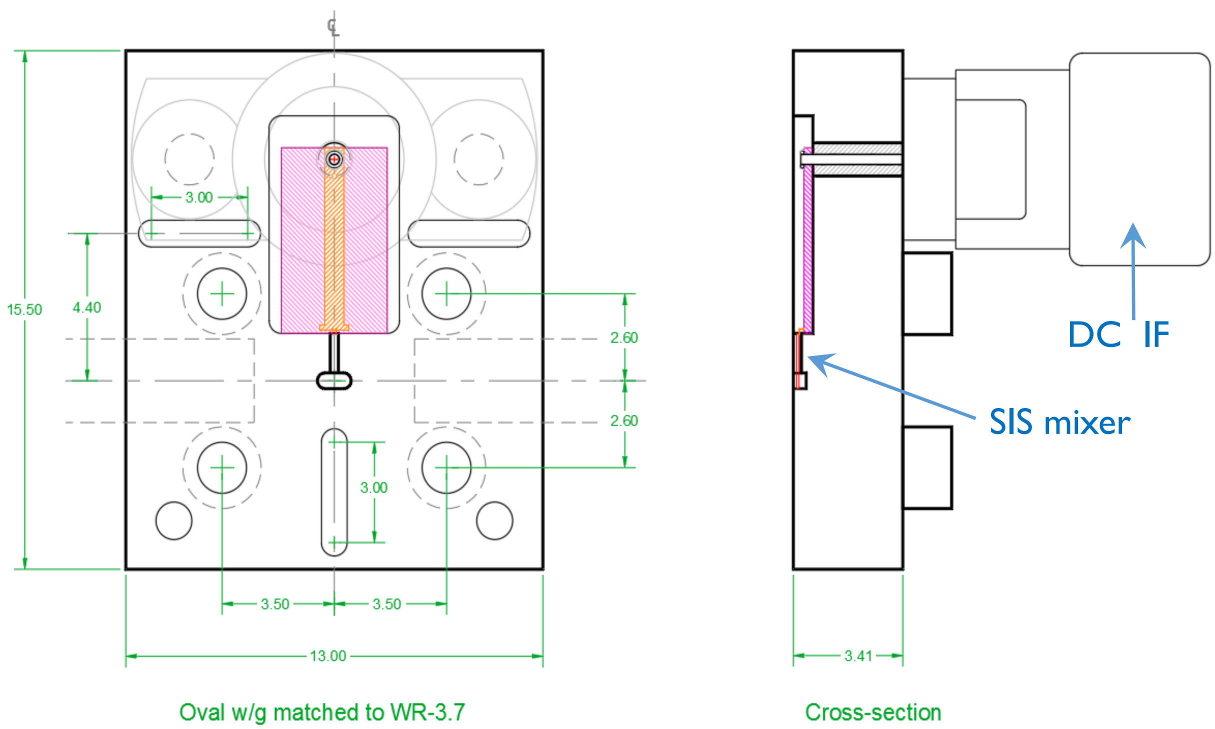

Fig. 2. A mixer chip module for use with the current Band-6 mixer chips. The modules will be modified to accommodate the new Band 6v2 chips when they are available.

Mixer test set

The existing mixer test sets at the NRAO CDL were designed with a 4-12 GHz IF. For the Band 6v2 development work we have replaced the IF components to accommodate the wider 4-16 or 4-20 GHz IF. An SAO 4-20 GHz isolator [1] is followed by 4-K and room temperature low-noise amplifiers and a spectrum analyzer with an integral low-noise preamplifier. A SP6T coaxial switch is also included in the cryostat to allow the IF stage to be connected to 4-K and heated loads for calibration.

IF amplifiers

During the course of this study it was noticed that the IF amplifiers from LNF would sometimes have a different gain when warmed up and cooled down again. This is shown in Fig. 3 for four different cool-downs.

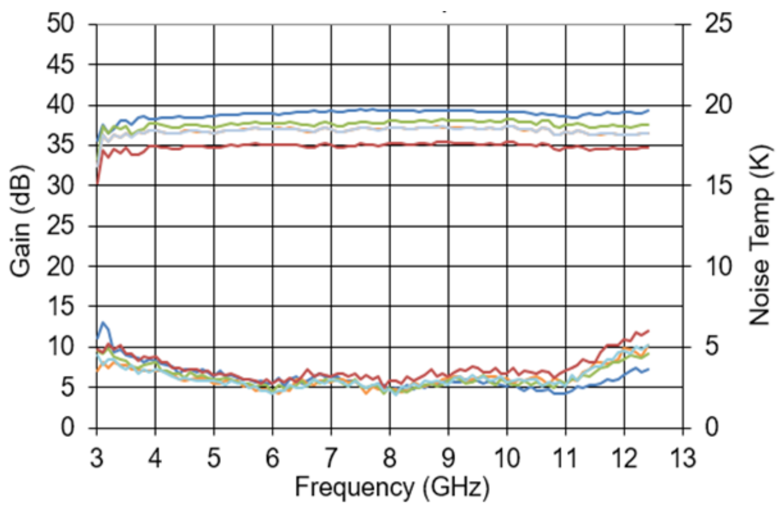

Fig. 3. Gain and noise temperature for the same LNF amplifier measured in four different cool-downs.

Superconducting IF quadrature hybrids

At the conclusion of the previous study, test wafers of 4-12 GHz quadrature hybrids had been made but the yield from the initial wafers was found to be very low. This was traced to the difficulty of making Nb vias between layers in a circuit with five layers in addition to the SiO_2 substrate (Nb, SiOx, Nb, SiOx, Nb). To remedy this the design was changed to use only two Nb layers. Fig. 4 shows the five-layer hybrid.

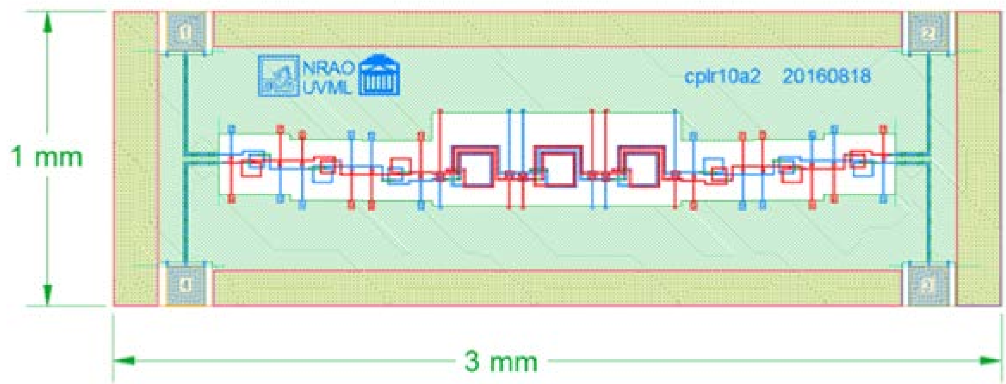

Fig. 4. The original five-layer 4-12 GHz quadrature hybrid. The layers are, stating on top of the SiO_2 substrate ant going up: Nb1 (blue); Nb2 ground plane (green); Nb3 (red). Gold areas are gold on the edges of the ground plane.

The design was modified by adding additional vias between layers which allowed the elements of the upper Nb layer Nb3 to be moved to to Nb2 or Nb1. At the end of the study period it had been fabricated but was not tested.

SAO isolator S-parameter measurement

The S-parameters of the SAO isolator [1] were measured at 4-K. To correct for reflections on the cables and transitions between the room temperature VNA calibration plane and the isolator, Keysight's Automatic Fixture Removal (AFR) procedure was used. AFR is an approximate procedure and measurements to estimate the uncertainty of our results are described in detail in [2]. Fig. 5 shows the magnitudes of the S-parameters at 4 K.

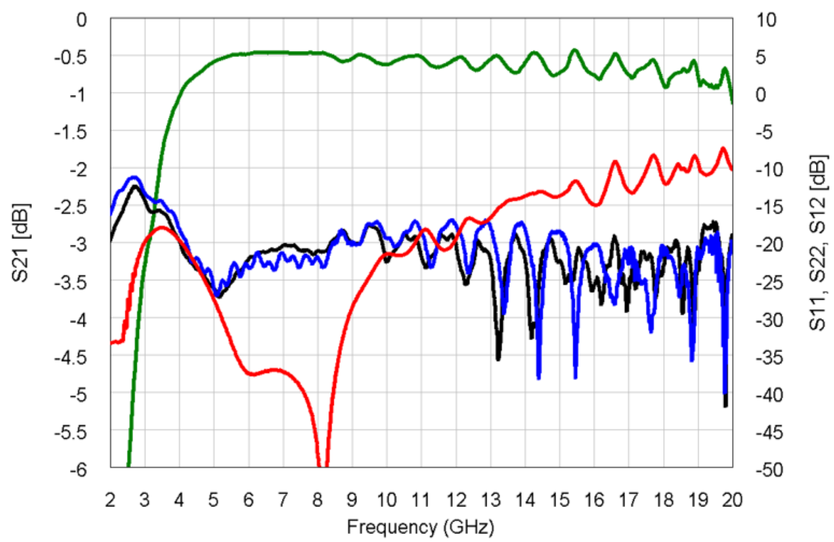

Fig. 5. Measured S-parameters of the SAO isolator:

- **Green trace: S21, insertion loss -- (left scale).**
- **Red trace: S12, isolation – (right scale).**
- **Blue trace: S11, input reflection coefficient – (right scale).**
- **Black trace: S22, output reflection coefficient – (right scale).**

SAO Isolator with LNA

To determine the degree of noise added by an SAO isolator [1], a Low Noise Factory LNF-NC4-16B amplifier was measured with an SAO 4-20 GHz isolator at its input. The 4-K test set [3] developed under the previous study project was used (Fig. 6). The result is shown in Fig. 7. It is seen that the added noise is typically 1 to 2 K, which will add several times that to T_{Rx} of a 2SB receiver.

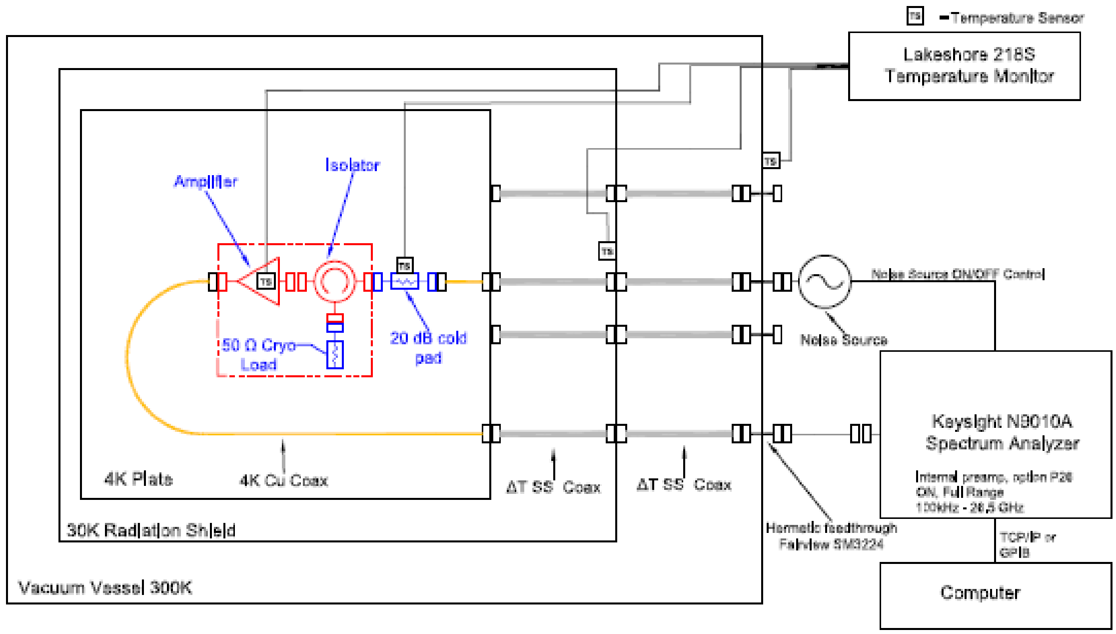

Fig. 6. The 4-K amplifier noise and gain test set.

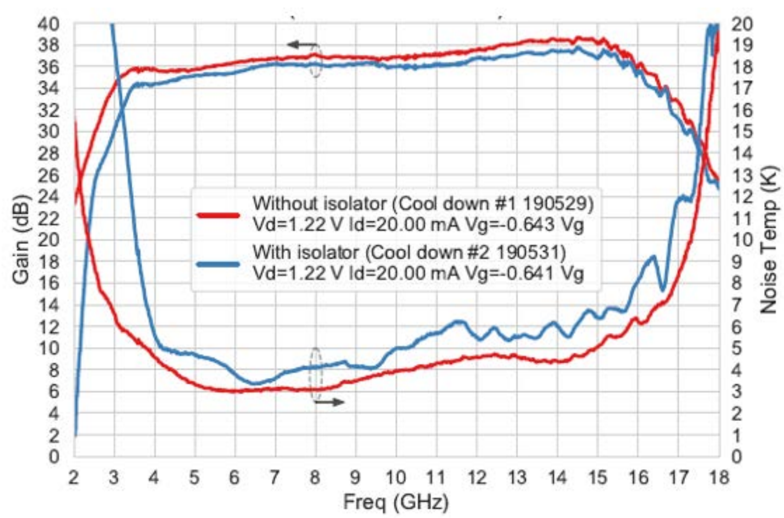

Fig. 7. Gain and noise temperature of a Low Noise Factory LNF-LNC4-16B amplifier with an SAO 4-20 GHz isolator at its input.

LO coupler

As shown in Fig. 8, The LO couplers in the current Band 6 SIS mixers consist of four gold coupling probes 0.1 x 0.3 mm, glued to 102 x 102 x 76 µm quartz standoffs. These are difficult to assemble and can occasionally become detached from the mixer block. A better scheme will have the probes printed on thin silicon membranes, an approach we have used successfully in experimental 385-500 GHz SIS mixers. This is shown in Fig. 9. Work on the Band 6v2 LO coupler has been delayed by the Covid-19 epidemic.

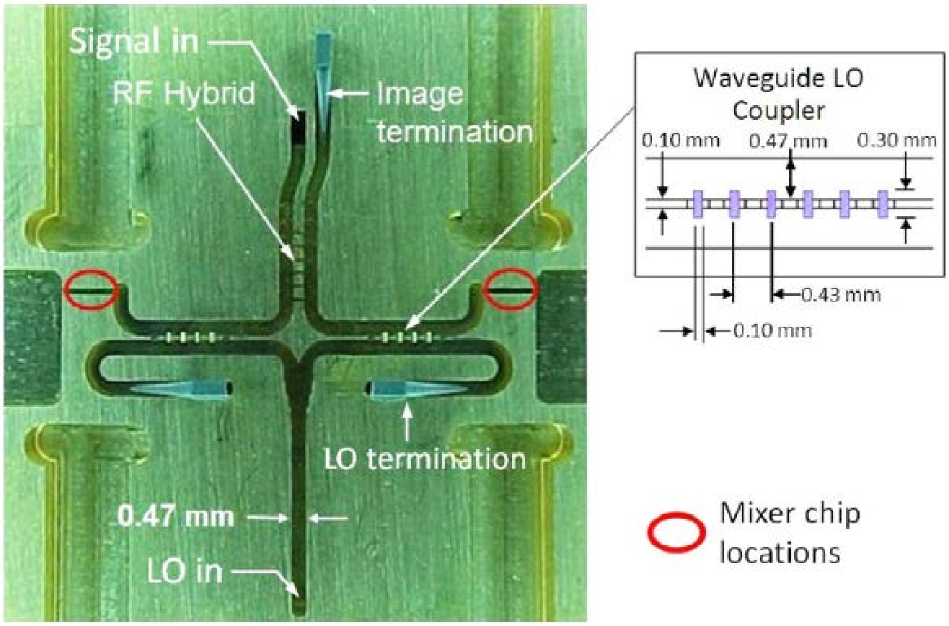

Fig. 8. The LO couplers in the current Band 6 SIS mixers.

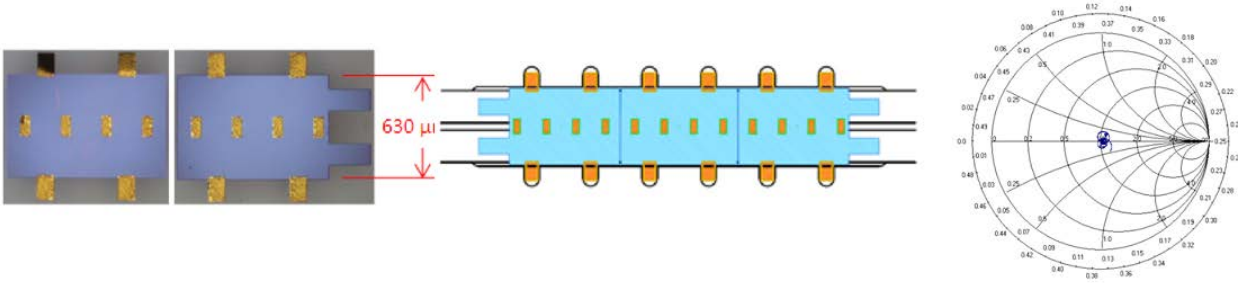

Fig. 9 Silicon membrane LO coupler for 385-500 GHz. Coupling is 20, 16, or 10 dB for 1, 2, or 3 modules. The Smith chart shows the reflection coefficient of the coupler across the full band.

RF quadrature hybrid

The present Band 6 mixers have branch-line quadrature hybrids machined in the input waveguide circuit. The branch line waveguides are 518 µm deep x 122 µm wide, and require special small diameter end mills with long working depth. To improve the image rejection of the Band 6v2 mixers it is planned to use superconducting coplanar waveguide hybrids on silicon (SOI) membranes. These drop-in hybrids will mount in shallow channels in the mixer block and be held in place by gold beam leads. The design will be based on the one successfully used for experimental single-chip balanced and sideband separating SIS mixers [4][5] as shown in Fig. 10, modified to work over the wider RF band of Band 6v2, and with the original thick quartz substrate replaced with a SOI membrane with gold beam leads.

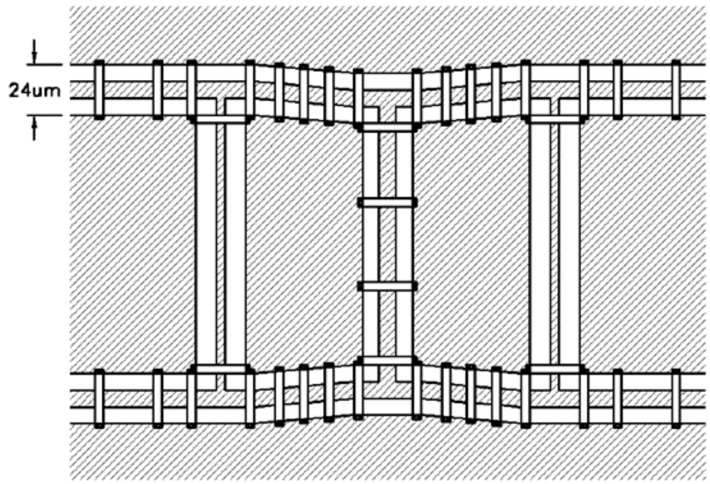

Fig. 10. The quadrature hybrid used for experimental fully integrated single-chip balanced and sideband separating SIS mixers. The design will be modified to allow the original thick quartz substrate to be replaced by a SOI membrane with beam leads.

The new design is under way, but fabrication has been delayed by the Covid-19 epidemic.

Conclusion

Accomplishments of this project are:

- New SIS mixers have been designed for operation over a wider 211-280 GHz RF band and with flatter noise temperature over an expanded 4-16 GHz or 4-20 GHz IF band. Fabrication of the mixers is delayed by the Covid-19 epidemic.
- A chip module has been designed to allow DC and RF measurements to be made on individual SIS mixer chips before selecting well matched pairs of chip modules for each 2SB mixer.
- Gain variations from one cool-down to the next were measured.in the best performing MMIC cryogenic low-noise IF amplifiers. This will limit the receiver configurations in which those amplifiers can be used on ALMA.
- The S-parameters of a 4-20 GHz edge-mode ferrite isolator has been measured at 4 K.

- The noise temperature of a low-noise amplifier with and without a 4-20 GHz edge-mode ferrite isolator has been measured at 4 K over 2-18 GHz. The 1-2 K contribution will significantly increase the overall receiver noise temperature.
- An RF quadrature hybrid on a silicon membrane substrate is being designed.
- A drop-in LO coupler on a silicon membrane substrate has been delayed by the Covid-19 epidemic.

Goals:

1. Design & fabricate B6v2 SIS mixer chips
2. Design & fabricate a chip module for the B6v2 chips
3. Complete the design of a balanced IF amplifier with superconducting quadrature hybrid chips.
4. Design a balanced mixer using the new SIS chips
5. Design a 180-degree IF hybrid for the balanced mixer.
6. Design a Si membrane RF quadrature hybrid
7. Design a Si membrane LO coupler.
8. Design the magnet circuit for the B6v2 SIS mixer.

Results:

1. A set of SIS mixer designs on Si membrane (SOI) substrates was completed for Nb/Al-AlOx/Nb and Nb/Al-AlN/Nb junctions. A mask set was purchased and delivered to UVML. Fabrication has been delayed by the Covid-19 restrictions.
2. A chip module for the SOI mixer chips has been designed.
3. (a) The balanced IF amplifier from LNF was found to have gain variations from one cool-down to the next. LNF has been working to solve this problem but have not yet done so. This limits the usefulness of the current LNF amplifiers. (b) The via resistance found in the superconducting IF quadrature hybrid chips was been eliminated by modifying the original three-Nb-layer design to have only two Nb layers. IF testing was not possible because of the Covid-19 restrictions.
4. After this proposal was submitted, funding was obtained to design an LO module (Warm Cartridge Assembly) with reduced LO sideband noise. This would obviate the need for balanced mixers and considerably reduce the cost of the B6v2 front ends. Work on balanced mixers was not continued.
5. Without the balanced mixers, the 180-degree IF hybrid is no longer needed.
6. An RF quadrature hybrid on a Si membrane substrate has been designed. Layout of the mask set and fabrication of the hybrids have been delayed by the Covid-19 restrictions.
7. The Si membrane LO coupler design and fabrication have been delayed by the Covid-19 restrictions. This component will be scaled from an earlier 385-500 GHz design and has no significant risk.
8. Work on the magnet circuit has been delayed by the Covid-19 restrictions. The magnet circuit is a simple modification of the current Band-6 magnet circuit and has no significant risk.

References

[1] Zeng, L., Tong, E., Blundell, R., Grimes, P., and Paine, S., "A Low-Loss Edge-Mode Isolator With Improved Bandwidth for Cryogenic Operation," IEEE Trans. MTT-66, no. 5, May 2018. https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=8291832

[2] P. Dindo, "S-Parameter Measurements of an SAO Edge-Mode Isolator at 4 K," Electronics Division Technical Note No. 224,, National Radio Astronomy Observatory, Charlottesville, VA 22903, Nov. 2019. http://library.nrao.edu/public/memos/edtn/EDTN_224.pdf

[3] J. Lambert "4-K Noise Measurements of LNF 4-16 GHz Amplifier with SAO Edge-Mode Isolator," Electronics Division Technical Note No. 225,, National Radio Astronomy Observatory, Charlottesville, VA 22903, Dec. 2019. http://library.nrao.edu/public/memos/edtn/EDTN_225.pdf

[4] A. R. Kerr, S.-K. Pan, A. W. Lichtenberger, N. Horner, J. E. Effland, and K. Crady, "A Single-Chip Balanced SIS Mixer for 200-300 GHz," Proceedings of the 11th Int. Symp. on Space Terahertz Tech., Ann Arbor, pp. 251-259, May 1-3, 2000.
http://search.space-thz.org/catalog/2000251259

[5] A. R. Kerr, S.-K. Pan, and H. G. LeDuc, "An integrated sideband separating SIS mixer for 200-280 GHz," Proceedings of the Ninth International Symposium on Space Terahertz Technology, pp. 215-221, 17-19 March 1998.
http://www.nrao.edu/meetings/isstt/papers/1998/1998215221.pdf