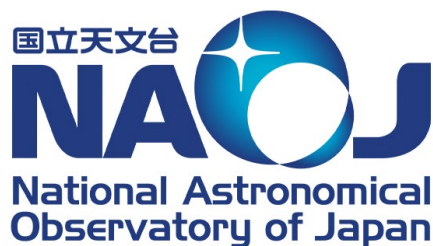


# Band-4+5 Receivers for ALMA 2030 Wideband Sensitivity Upgrade: initial concept and plan

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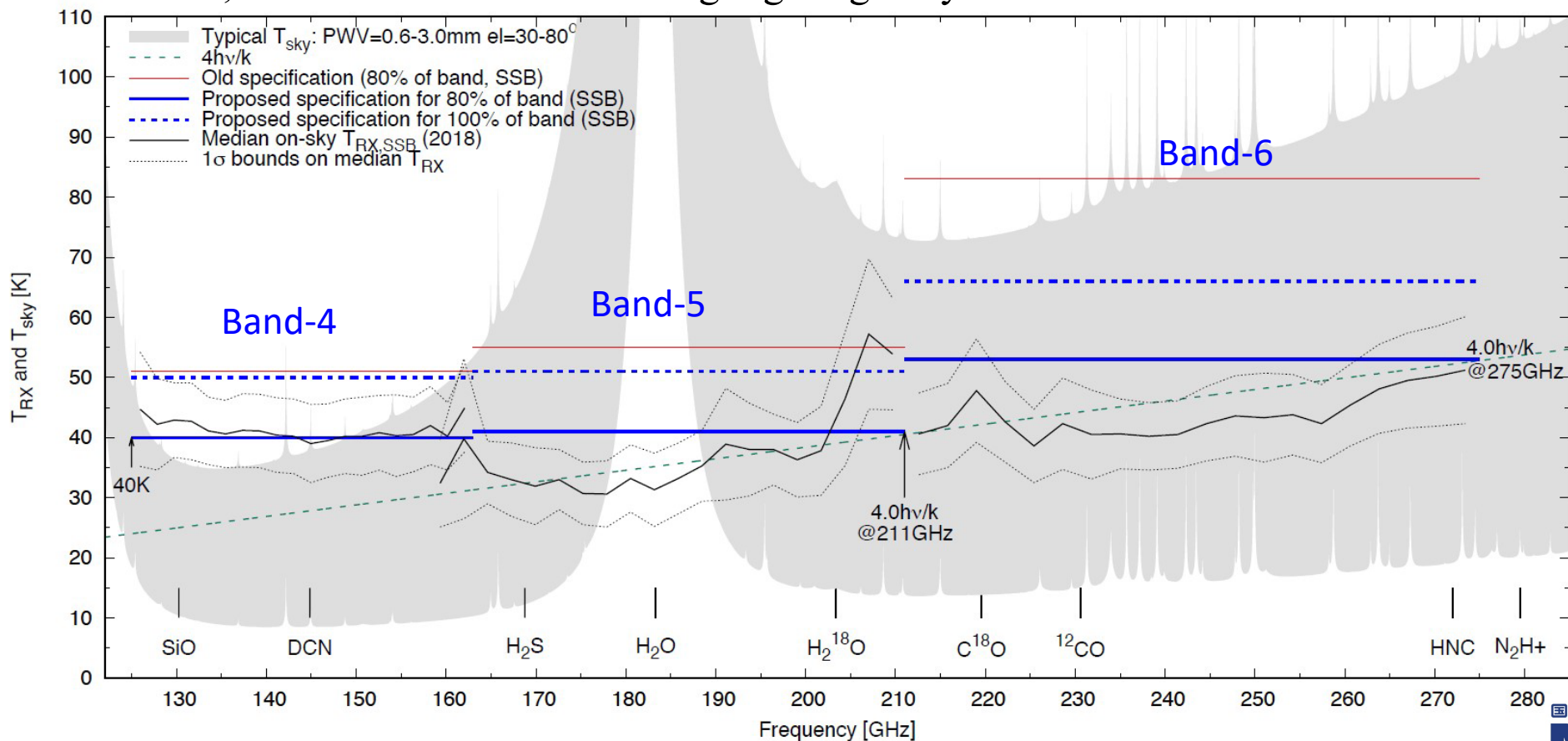


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# Motivation: Why ALMA Band-4+5?

- Present ALMA receiver bands are based on the technology in year 2000s, typical signal frequency range are set to 80% of waveguide bandwidth, or  $< 32\%$  fractional bandwidth for Band-3 to Band-8.
- Band-4 and Band-5 frequency boundary (163 GHz) nearly divides the frequency window between 125 – 183 GHz, thus it is difficult for tracing high- $z$  galaxy clusters.



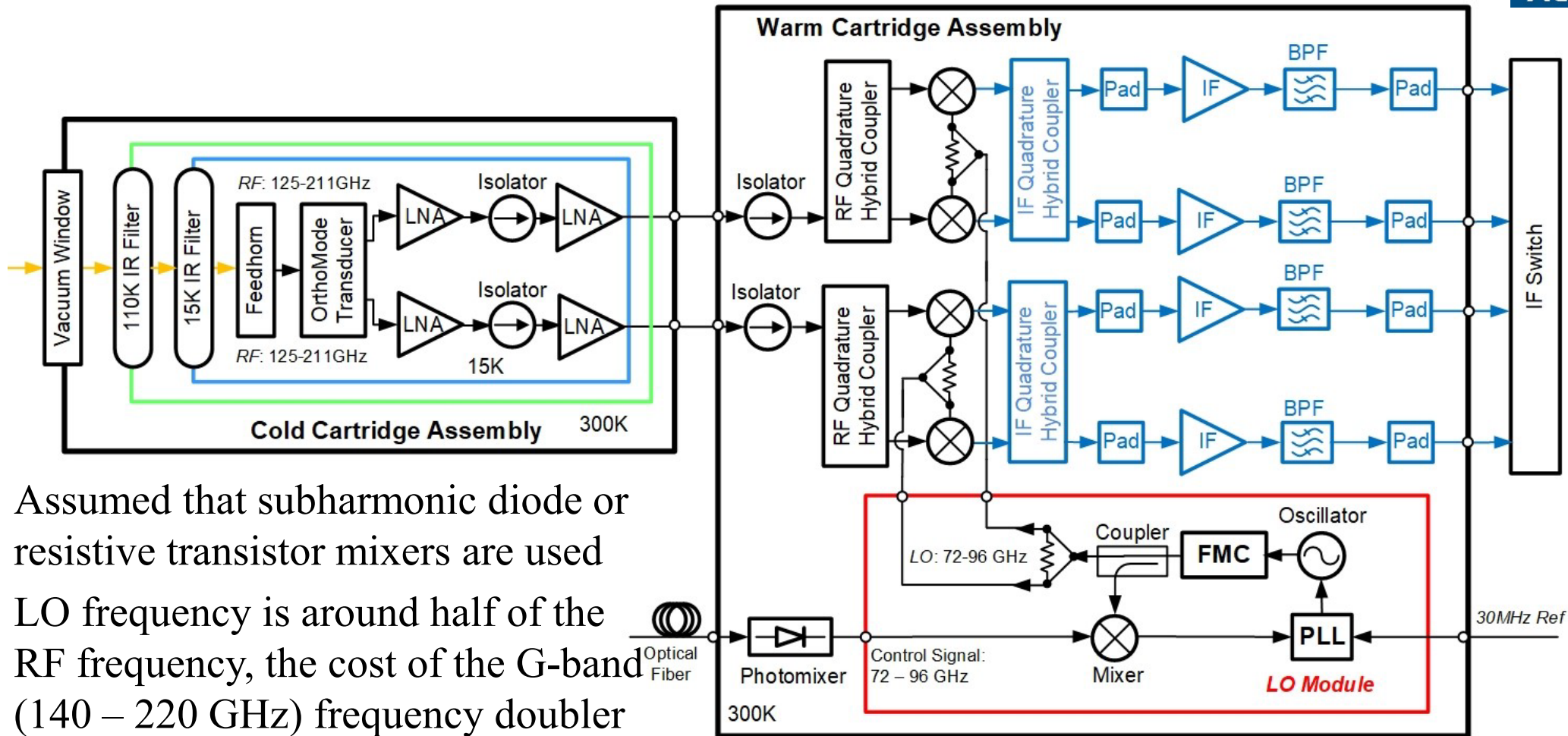


# ALMA Band-4+5 Specifications



- $f_{\text{RF}} = 125 - 211 \text{ GHz}$  (51.2%)
- Noise temperature = 4x quantum limit (at 211 GHz) for 80% of bandwidth, 5x quantum limit (at 211 GHz) for full-band,  $T_n < 41\text{K}$  for 80% BW,  $T_n < 51 \text{ K}$  full-band.
- Extend the existing 4-GHz IF bandwidth per sideband per polarization by 4 times up to 16 GHz. ( $f_{\text{IF}} = 4 - 20 \text{ GHz}$ ,  $f_{\text{IF}} = 3 - 19 \text{ GHz}$ , or  $2 - 18 \text{ GHz}$  for each IF channel)
- Sideband separation scheme (2SB), image rejection ration  $> 13 \text{ dB}$
- Local oscillators - to avoid possible LO-IF interference, shift the LO fundamental oscillator frequency to  $24 - 32 \text{ GHz}$ , integrated with frequency tripler and power amplifier, plase-lock at  $72 - 96 \text{ GHz}$ .

# Block Diagram: HEMT-Receiver Scheme



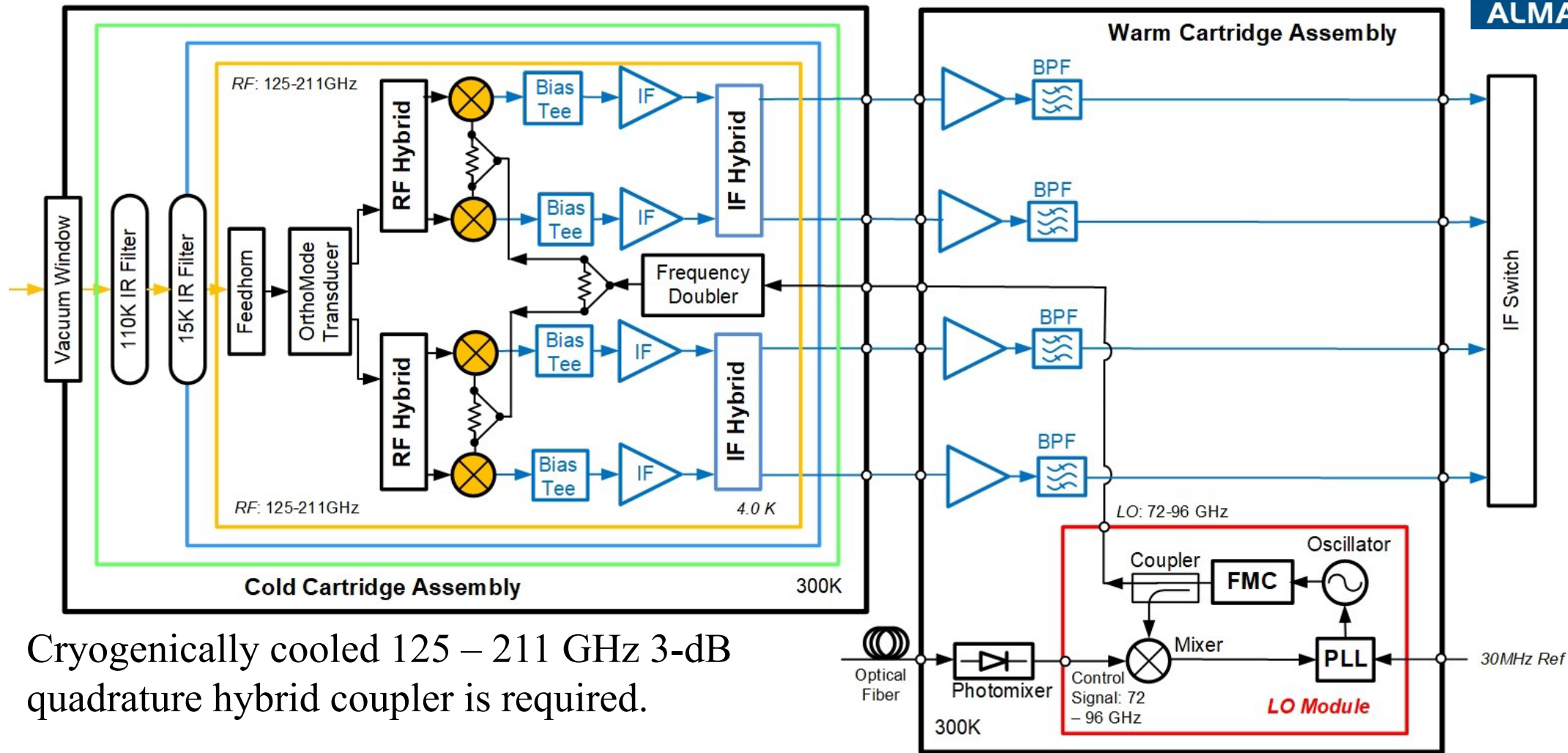
- Assumed that subharmonic diode or resistive transistor mixers are used
- LO frequency is around half of the RF frequency, the cost of the G-band (140 – 220 GHz) frequency doubler and power amplifier can be deduced

# Gain/Noise of HEMT-Rx: Initial Analysis

- Cold optics mirror pair + corrugated horn:  $T_{\text{optics}} < 4\text{K}$
- Assume that the noise contribution by the mixer/ down-converter  $\sim 1\text{K}$ , thus  $T_{\text{n,LNA}} < 41\text{-}5\text{K} = 36\text{K}$  for 80% BW (125 – 194 GHz),  $T_{\text{n,LNA}} < 51\text{-}5\text{K} = 46\text{K}$  fullband,  $G_{\text{LNA}} > 40$  dB.
- The band-2+3 receiver indicate that for millimeter-wave cryogenic low noise amplifier, 4x quantum limit noise is possible for small portion of frequency range. For band-4+5 case, try to optimize the noise performance around 194 – 211 GHz with 4.5x quantum limit, thus it is possible to meet the specification.
- *Advanced InP HEMT or MHEMT fab with transistors optimized for ultra-low-noise application is required.*

Frequency (GHz)	125	163	194	211
$4hv/k, T_n$ (K)	24.0	31.3	37.2	40.5
$4.5hv/k, T_n$ (K)	27.0	35.2	41.9	45.6
$5hv/k, T_n$ (K)	30.0	39.1	46.6	50.6

# Block Diagram: SIS-Rx Scheme



- Cryogenically cooled 125 – 211 GHz 3-dB quadrature hybrid coupler is required.



# Gain/Noise of SIS-Rx : Initial Analysis



- Cold optics Mirror pair + Corrugated horn:  $T_{optics} < 4K$
- SIS mixer gain  $G_{mix} \sim 0.9 - 0.95$ , noise  $T_{mix} \sim 6$  to  $10K$  for SSB
- IF CLNA  $G_{IF} = 32 - 34$  dB,  $T_{n, IF} = 3-5K$  typically,  $7K$  band edge
- Assume that conductor loss introduced by the RF quadrature hybrid  $\leq 1.5$  dB = 1.414, thus estimated receiver noise temperature

$$T_{rx} = T_{optics} + 1.414(T_{mix} + (1/G_m) * T_{n, IF})$$

- $T_{rx} = 4 + 1.414 * (6 + 1.11 * 5) = 20.3$  K for low-frequency, mid-IF band,
- $T_{rx} = 4 + 1.414 * (10 + 1.11 * 7) = 29.15K$  for high-frequency, high-IF band
- IF additional conductor loss of the RF quadrature hybrid = 3dB,  $T_{RX} = 39.56K$  for high-frequency edge.
- Cryogenically cooled, low-conductor-loss, ultra-wide bandwidth, highly amplitude and phase balanced quadrature hybrid for 125 – 211 GHz is as important as the the SIS mixers.



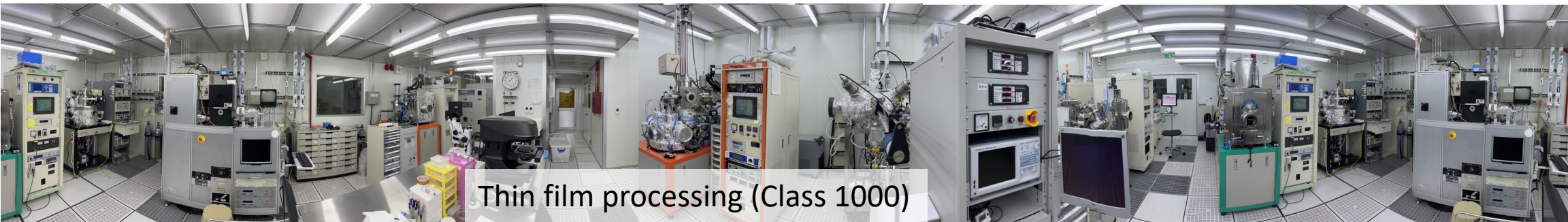
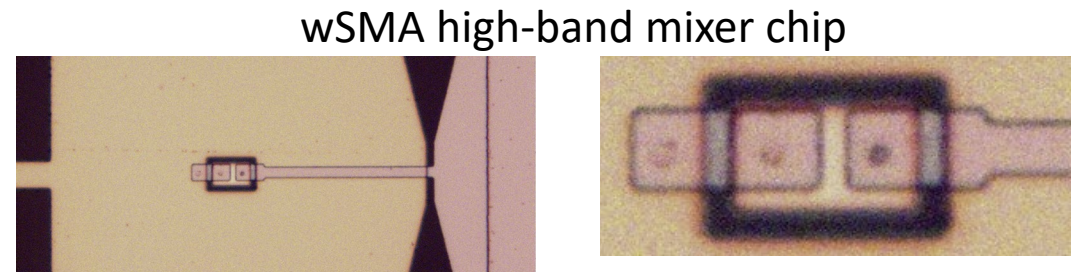
# Key Components to be Developed



- Corrugated horn antenna: revised design from Band 7+8 (275 – 500 GHz band), with modification to reduce the optical path
- OMT: scaled from existing 70 – 116 GHz turnstile junction OMT design with similar fractional bandwidth
- SIS mixers: high-Jc junction, series-connected twin-junction design
- SIS mixer block assembly: including RF hybrid couplers, LO power divider, and LO directional couplers
- RF cryogenic low-noise amplifiers (CLNAs) for 125 – 211 GHz: Fraunhofer Institute of High-Frequency Electronics (IAF) design using 35-nm MHEMT foundry, back-up solution: M/A-COM Europe (former OMMIC) 40-nm MHEMT, or NGST 35-nm InP HEMT
- RF quadrature hybrid coupler: early prototype design realized, new design to cover full 125 – 211 GHz band with even better input/output matching and isolation.

# SIS Junction Fabrication

- ASIAA started the superconducting device fabrication laboratory since 1995, the mixers developed was for SubMillimeter Array (SMA) in the beginning, the bands developed including the 176 – 256, 250 – 354, 320 – 425, and 600 – 696 GHz.
- For wider frequency coverage, high- $J_c$  junction ( $\sim 15 \text{ KA/cm}^2$ ) is required to reduce the junction capacitance.
- Niobium-AlO<sub>x</sub>-Niobium junctions will be fabricated on quartz substrate.

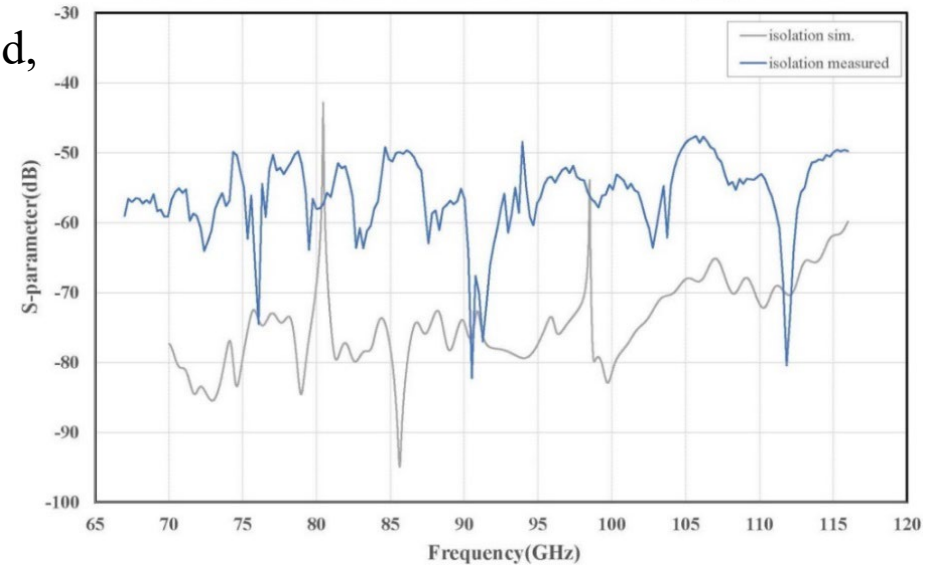


# Turnstile Junction OMT

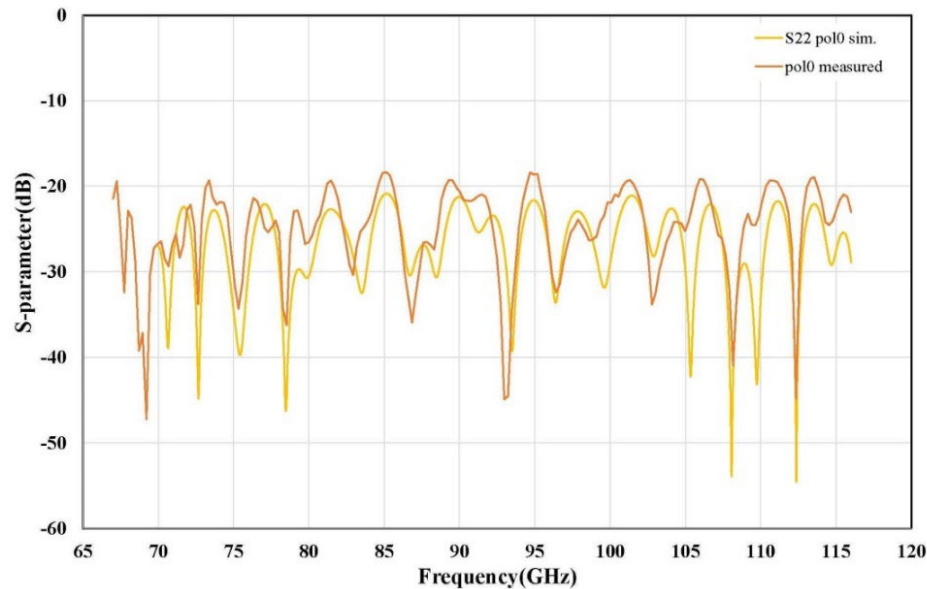
- 67 – 116 GHz WR-10 ver. fabricated and measured, 125 – 211 GHz version will be fabricated soon



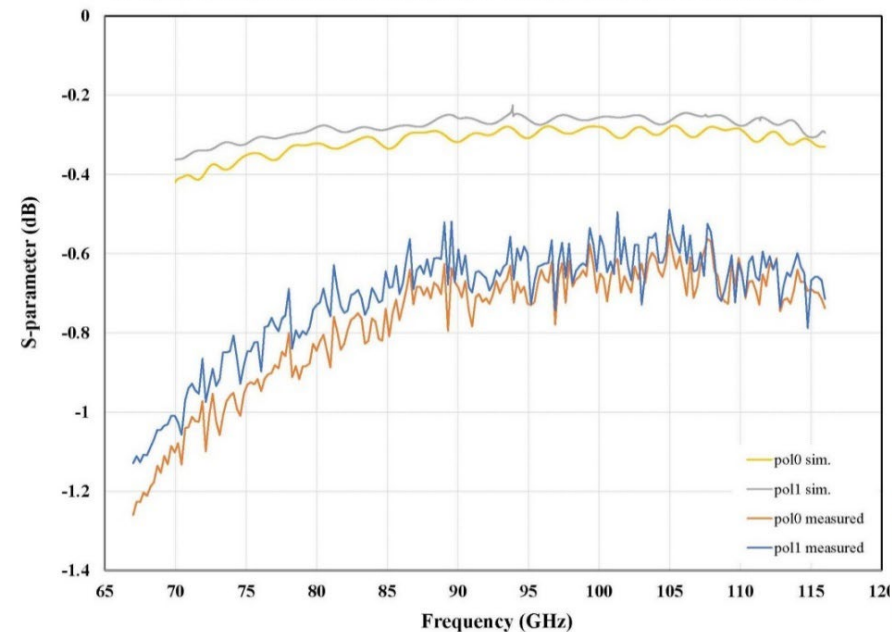
W-band Turnstile Junction Orthomode Transducer SN/01 output port isolation



W-band Turnstile Junction Orthomode Transducer SN/01 pol-0 Return Loss



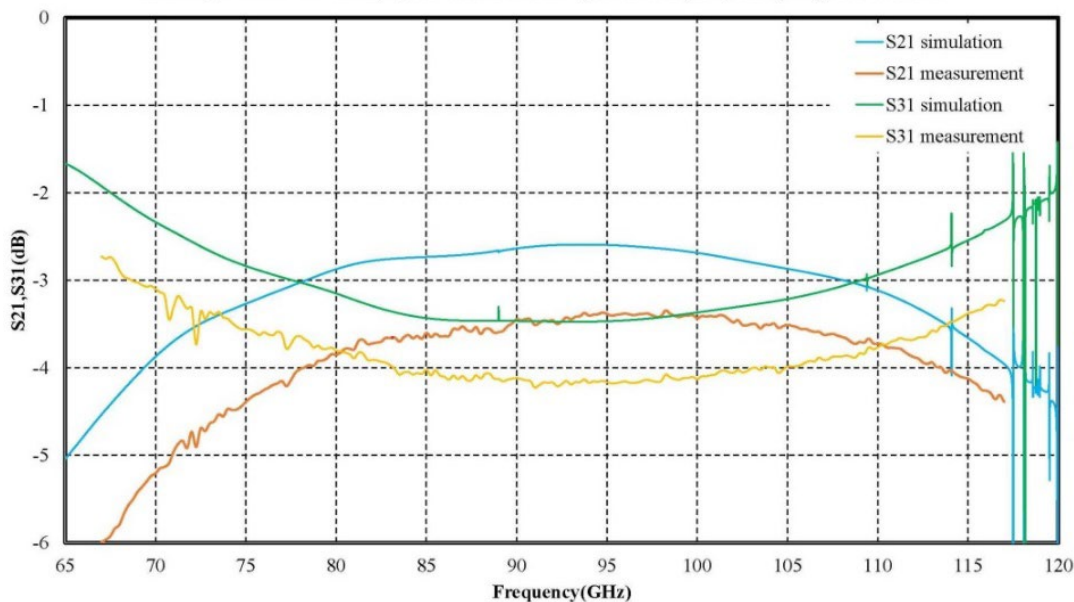
W-band Turnstile Junction Orthomode Transducer SN/01 Insertion Loss



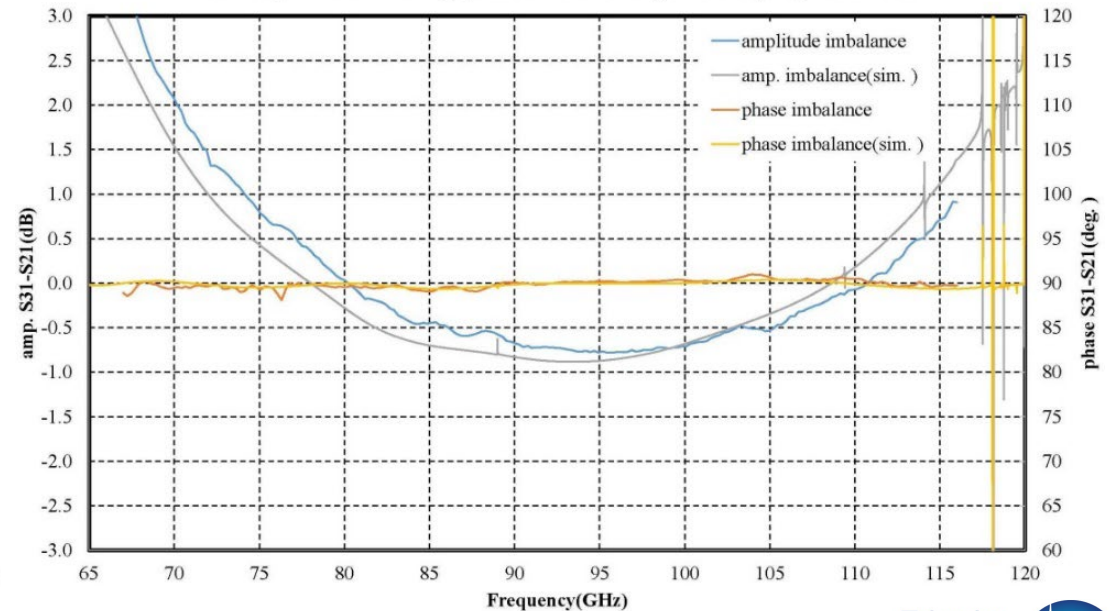
# RF Quadrature Hybrid Coupler (I)

- To speed up the development progress, we use existing W-band PNA to test scaled model in extended W-band with WR-10 flange, if the design fit to the specifications, then we scale the mechanical size by factor of 1.84 to get the design fit to Band-4+5.
- 12<sup>th</sup>-order, reduced-height broaden rectangular W/G, 74 – 116 GHz (44.2% BW), Maximum amplitude imbalance: 0.8 dB. Maximum phase error from 90 degree : 2.0 degree.
- Detail design will be presented in 2023 *Asia-Pacific Microwave Conference*, Taipei, Taiwan.

WR10QH12-73-115-P50, Quadrature 3-dB Hybrid Coupler, Coupling Coefficient

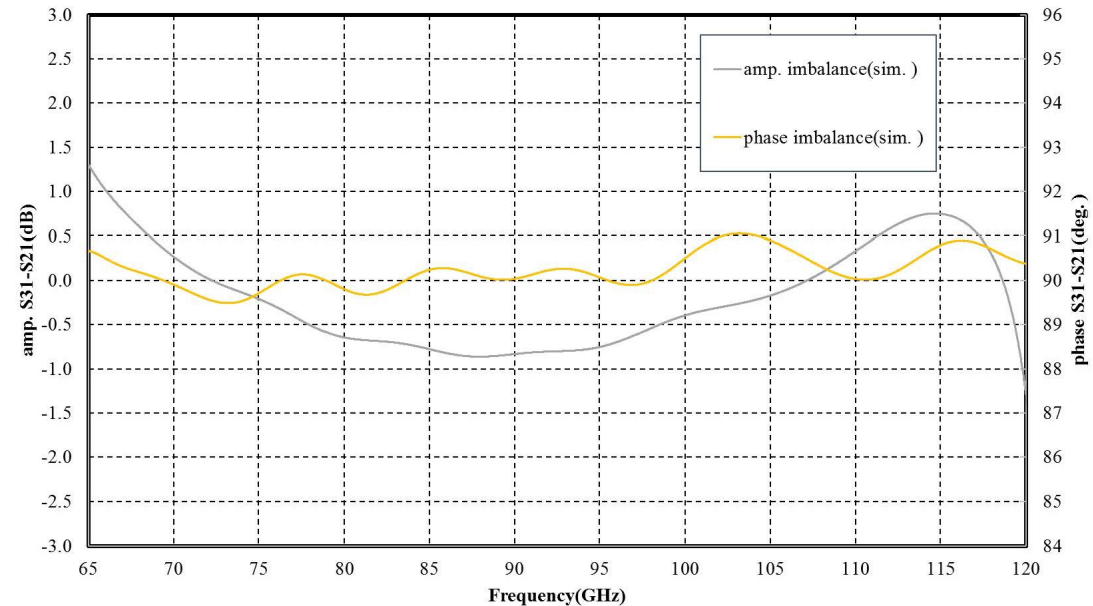
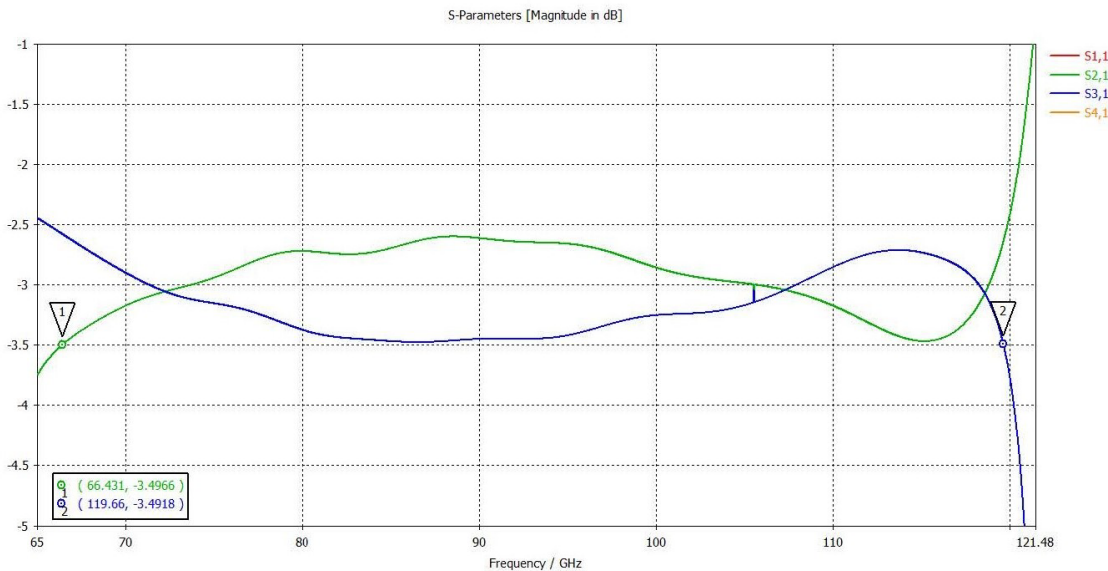
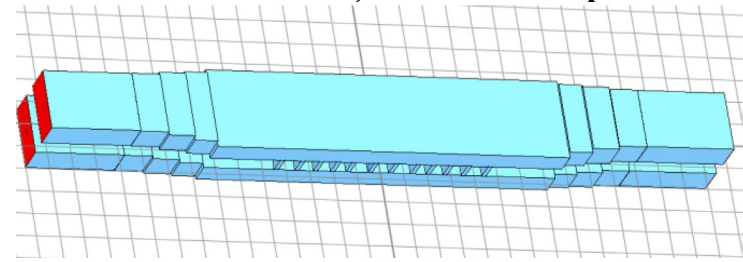


WR10QH12-73-115-P50, Quadrature 3-dB Hybrid Coupler, Imbalance



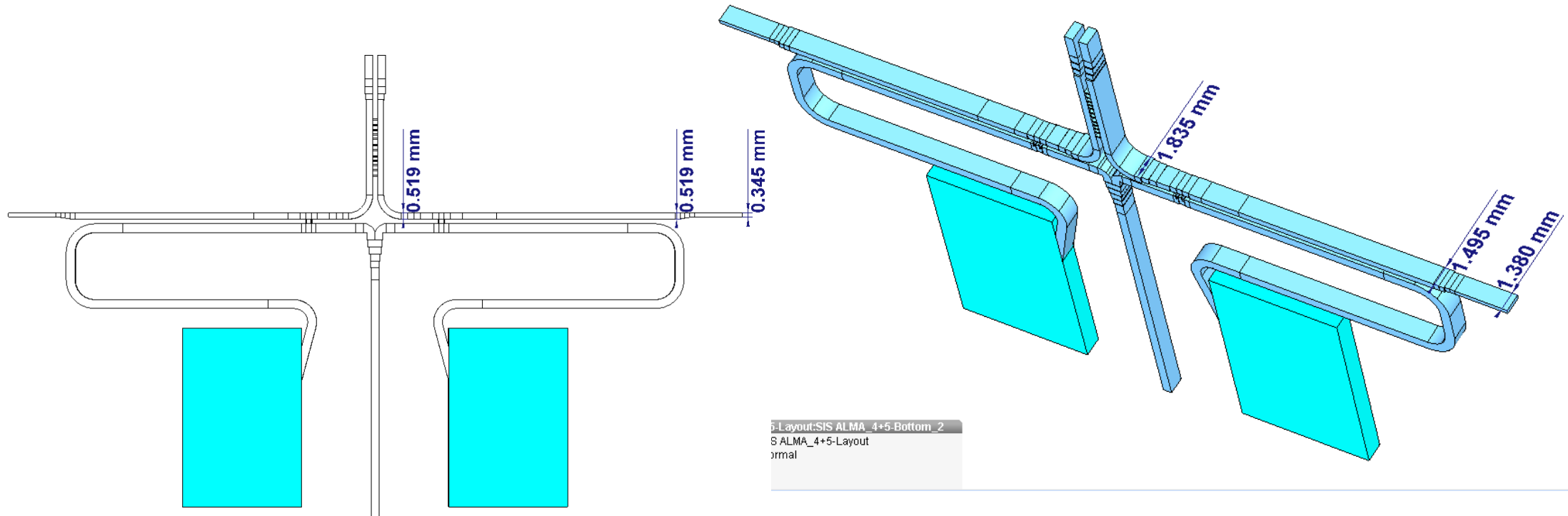
# RF Quadrature Hybrid Coupler: Final Version

- Most-recent design progress: **57% bandwidth**,  $\pm 0.9$  dB amplitude imbalance,  $\pm 1.0$  degree phase imbalance design. Extended W-band design (66.5 – 119.5 GHz) for conceptual verification is now fabricating in machine shop.

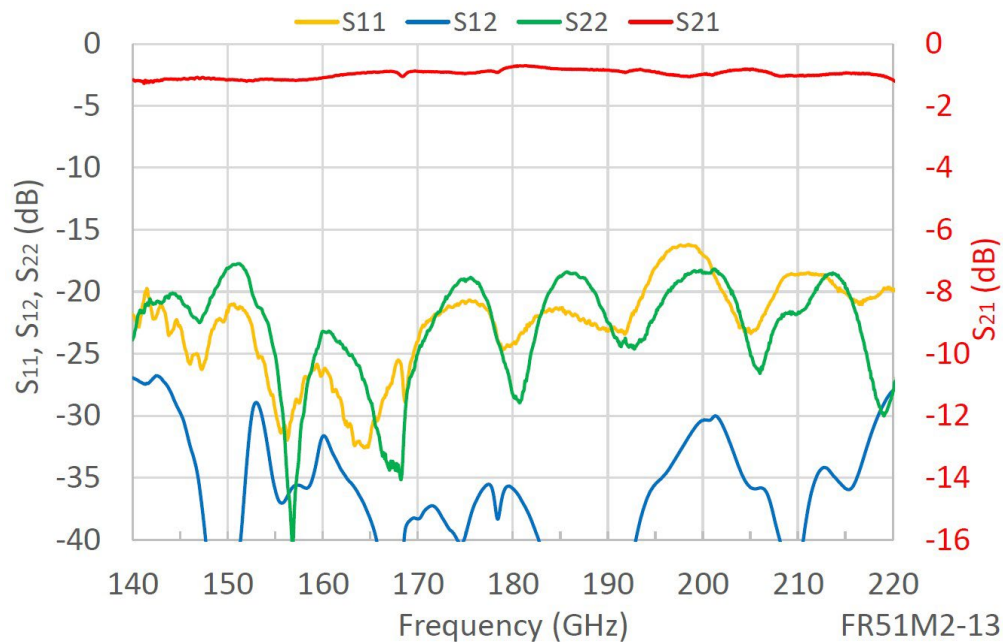


# RF Quadrature Hybrid + LO Divider/ Coupler

- LO divider / 17- dB coupler for 144 – 192 GHz is also designed, with integrated RF (123 – 220 GHz) quadrature hybrid to form the RF/LO signal/power assembly for SIS prototype receivers. EM simulation is completed and mechanical drawing for fabrication is now under progress.

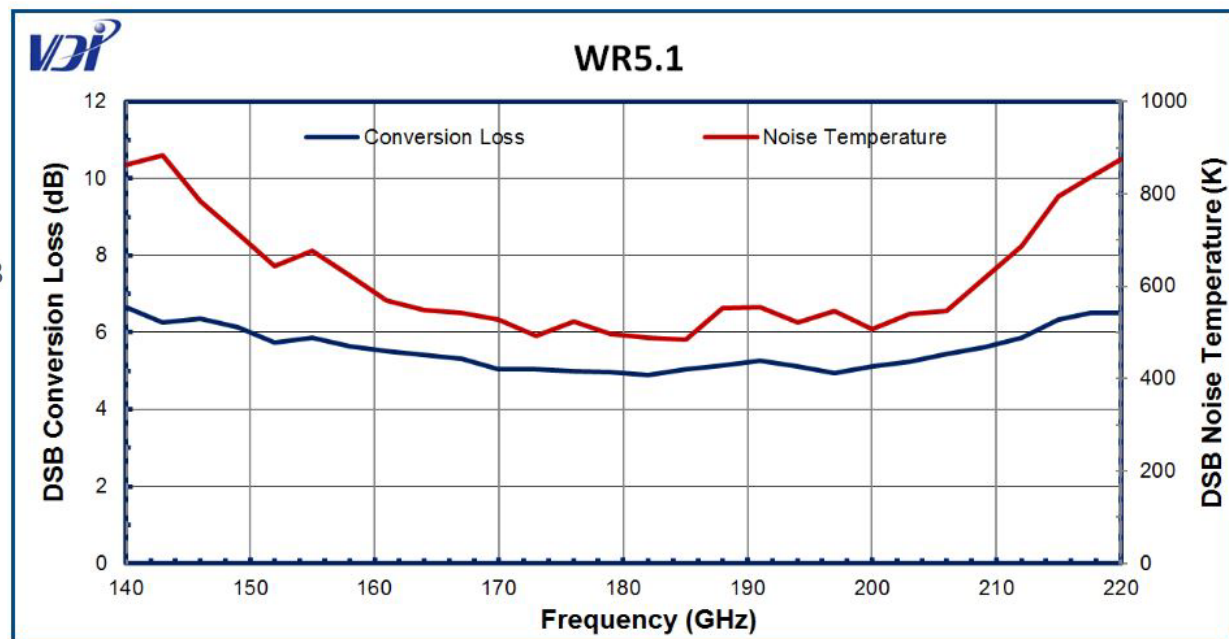


# RF Isolators and Diode Mixers



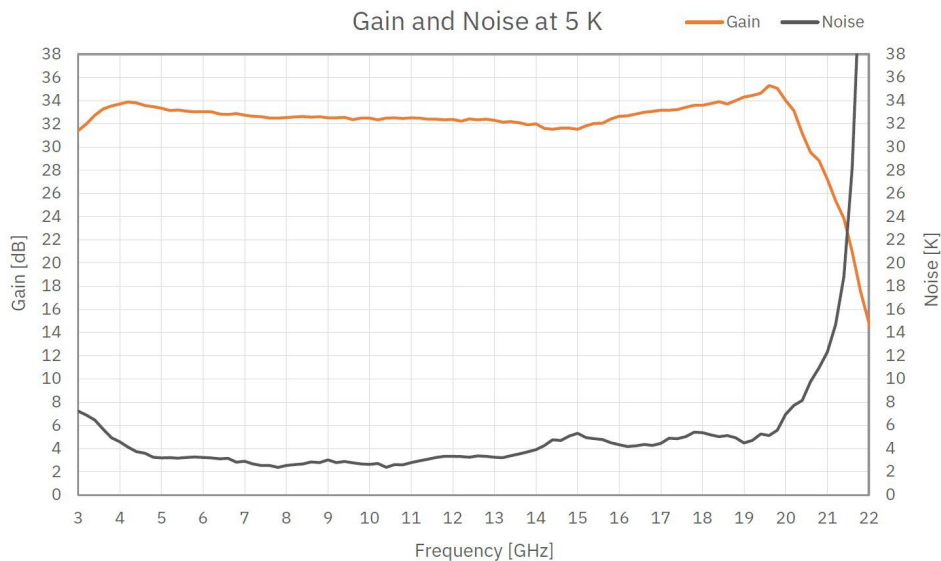
- Mixer candidate: Virginia Diodes Inc. WR5.1SHM
- Single sideband conversion loss 8 – 10 dB expected for 140 – 220 GHz, but unknown for 125 – 140 GHz
- Need to confirm the RF 1-dB power compression point

- FR51M2 Room-temperature version is available from Microharmonics Inc., USA. Cryogenic version is still under development.



Results achieved with optimized LO power

- IF LNA candidate: Low-Noise Factory LNF-LNC6\_20D (cryogenic version) and LNF-LNR6\_20B\_SV, originally for 6 – 20 GHz, but the datasheets shows flat gain, low noise and good input / output matching for 4 – 20 GHz



- IF Quadrature Hybrid candidate: Marki QH-0226

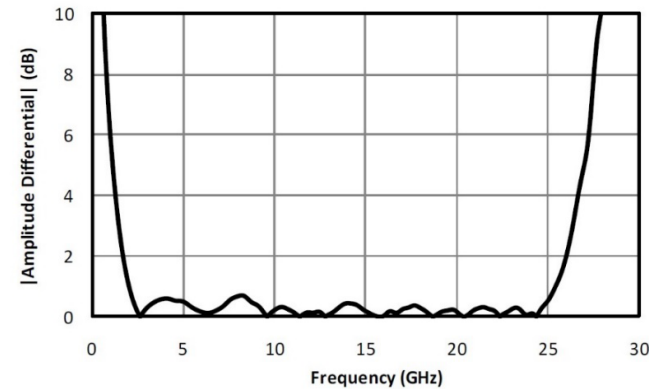


Fig. 3. Amplitude difference between the 0° and 90° output ports.

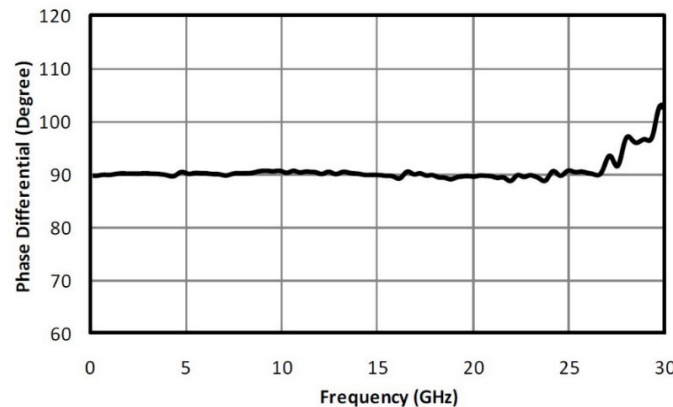


Fig. 4. Phase difference between the 0° and 90° output ports.

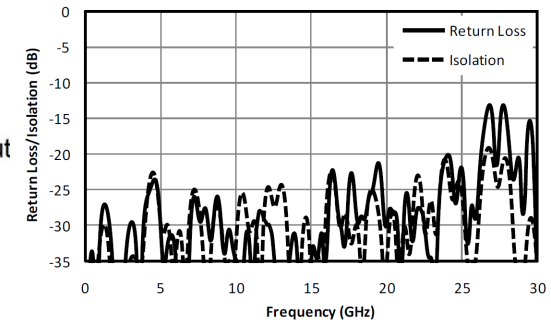
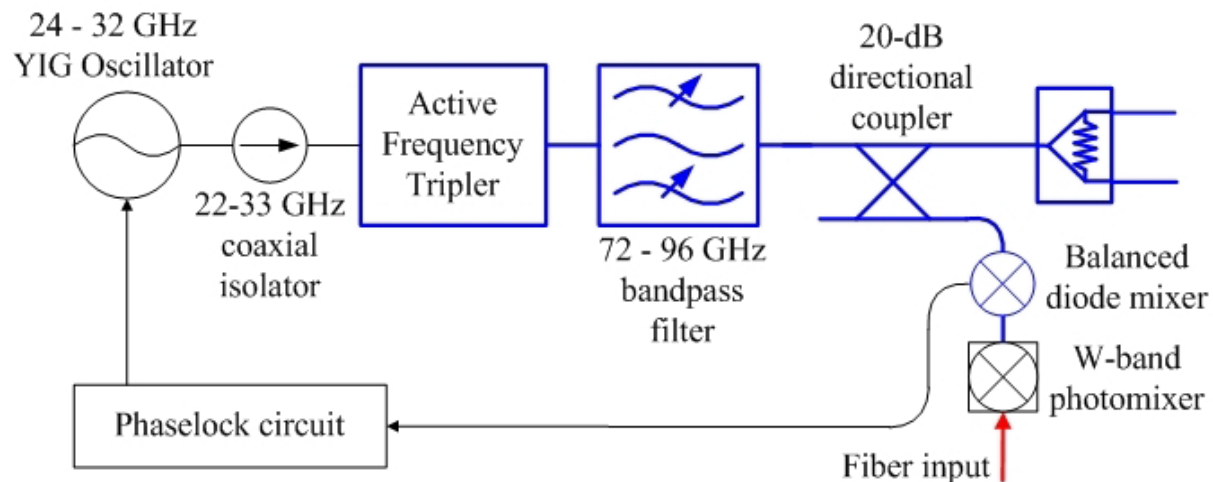
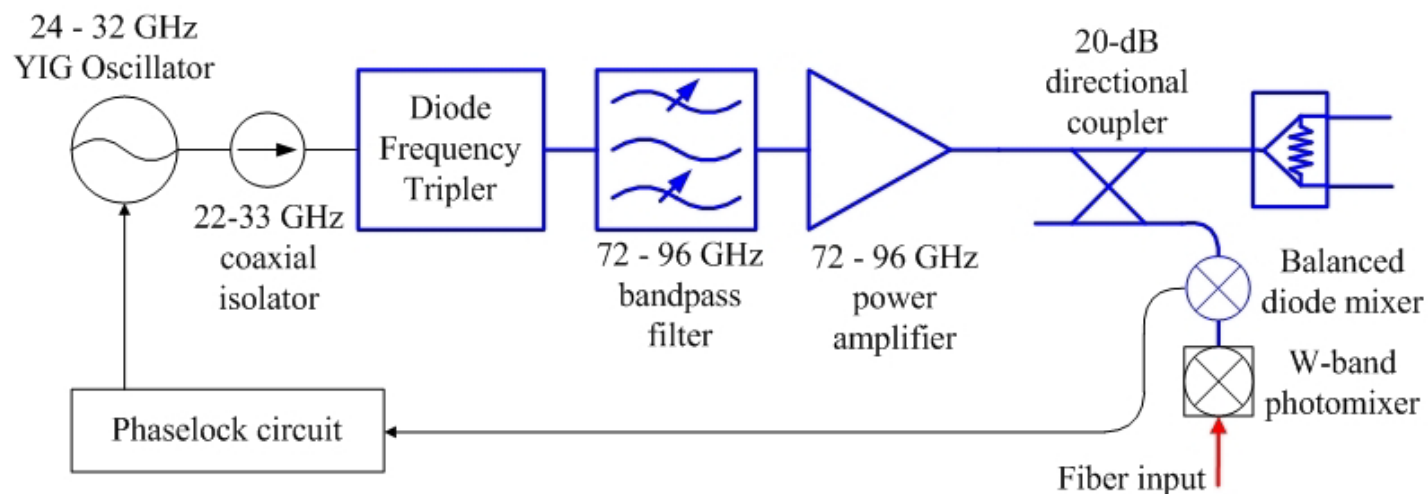


Fig. 2. Typical port return loss and isolation (all ports 50 Ω terminated).

To avoid overlap of LO fundamental frequency range to IF frequency range set the YIG oscillator frequency  $> 20$  GHz.



RF signal source will have broader tuning bandwidth based on 20 – 36 GHz YIG oscillator, cascaded with an additional 125 – 220 GHz frequency doubler





# Near Future Plan



- Orthomode transducer, RF quadrature hybrid coupler, and LO Power divider and coupler (as SIS mixer input assembly) is just finish the EM simulation, mechanical design will be ready by early Nov. 2023, target to have the first set of SIS mixer input assembly ready for test by Feb. 2024.
- SIS mixer design is in initial phase, will have the SIS junction fabrication by March-May 2024.
- First prototype of SIS-based receiver CCA + WCA cartridges will be constructed after July 2024.
- HEMT-based receiver will strongly depends on the collaboration on the design and fabrication of the HEMT cryogenic low-noise amplifiers for 125 – 211 GHz, initial contact with the MHEMT foundry is positive. Need further cooperation and development.