Receivers for the Black Hole Explorer

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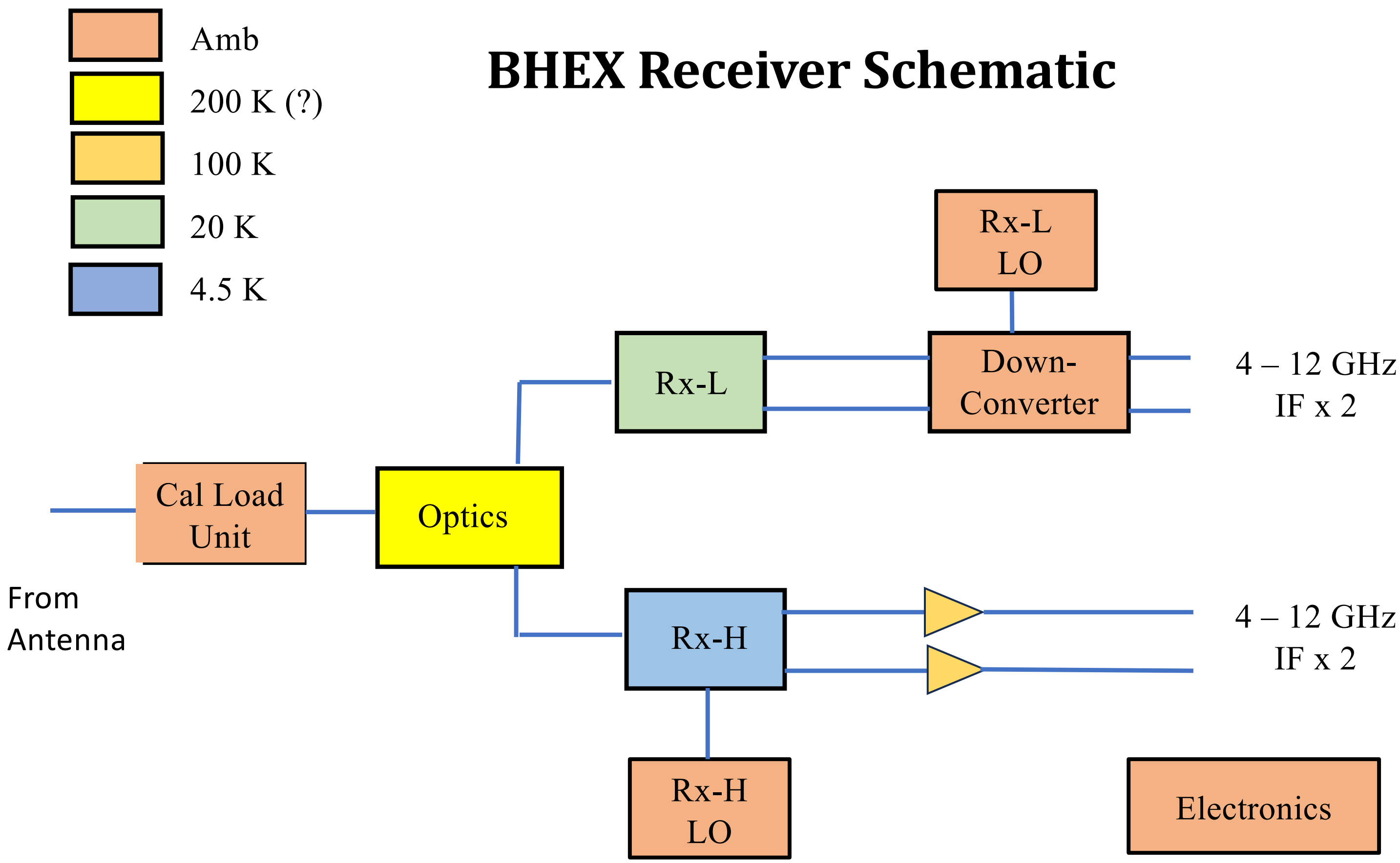
Receiver Configuration at a Glance

	Rx-H	Rx-L
Type	SIS	HEMT
Sky Frequency	240† - 320 GHz	80 - 106.6 GHz
Physical Temp	4.5 K	20 K
IF	4 - 12 GHz	4 - 12 GHz
LO Frequency	252 - 308 GHz	38 - 48 GHz*
Output	DSB	USB
Target Noise Temp.	25 - 30 K ($2h\nu/k$)	40 - 50 K

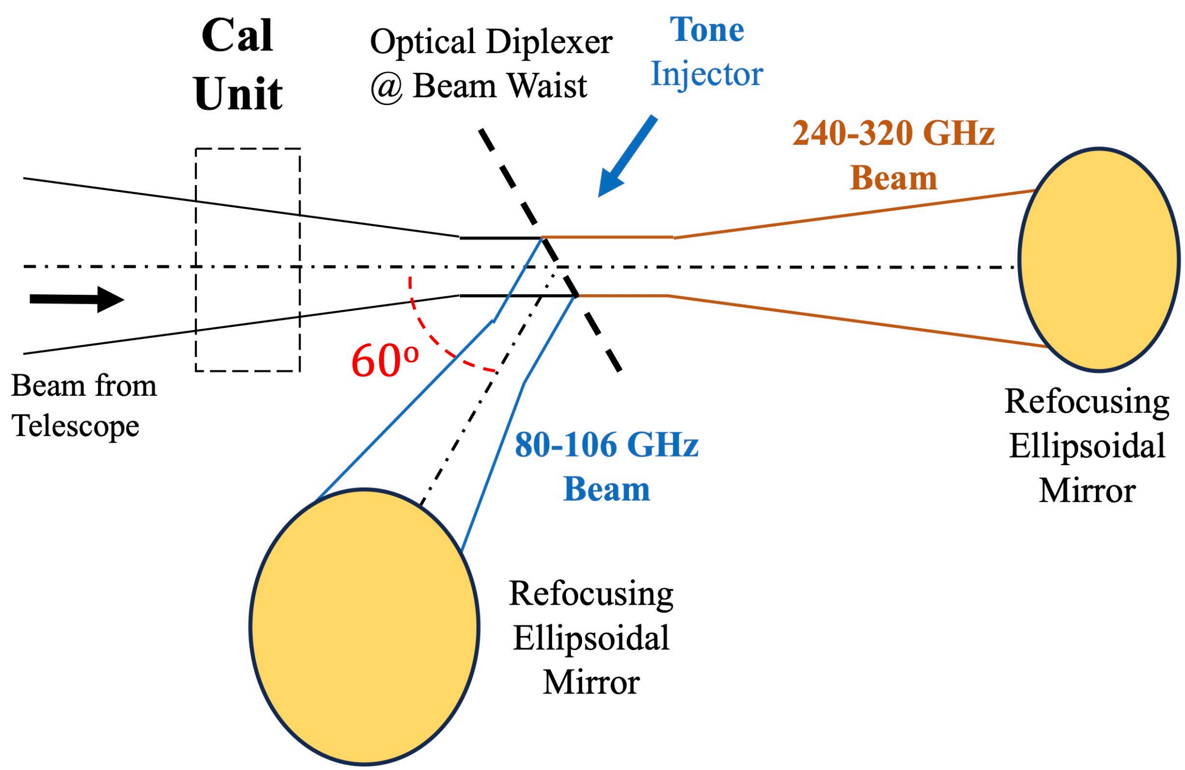
- Rx-L is used to locate fringes and for FPT
- Second harmonics mixer used for Rx-L.

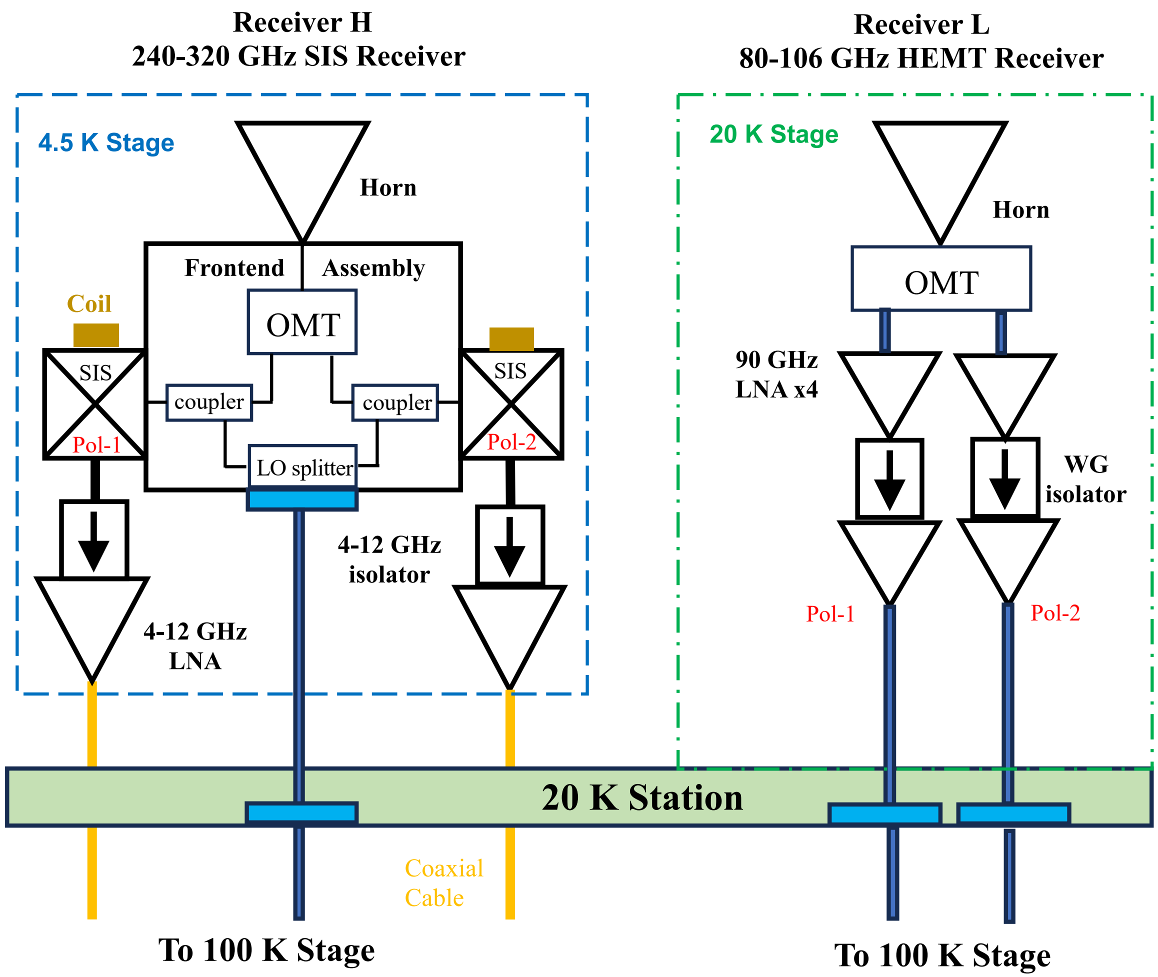
† Possibility to be go down to 220 GHz

BHEX Receiver Schematic



Optics Layout at a Glance





Receiver Layout Inside the Cryostat

- The 4-12 GHz LNAs are to operate with 1 mW of power dissipation each to limit thermal load.
- A 2nd stage amplification is needed on the 100 K stage.

Why Single Band (240-320 GHz) SIS Receiver?

Pro

- Reduced Thermal Budget for Cryostat.
- Reduced complexity and cost.
- Only a single LO source is required – Standard commercial WR-3.4 LO covers 220– 330 GHz.
- Can take advantage of wideband SIS technology to expand sky frequency coverage to 220 GHz beyond 240 GHz baseline.

Con

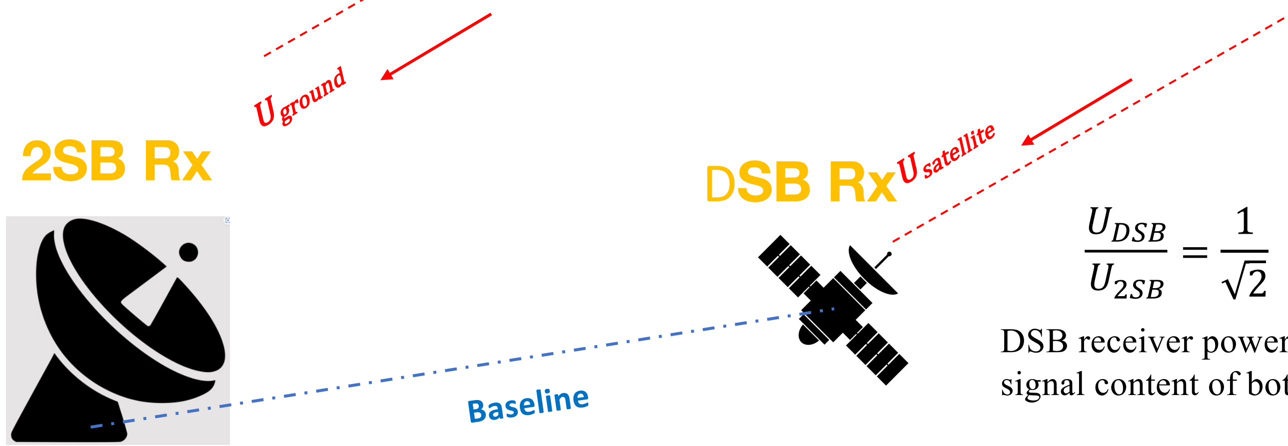
- Non-standard SIS Band: ALMA B6 210-275 GHz; ALMA B7 275-375 GHz.
- No 345 GHz coverage.
- Standard EHT tuning is LO 228 GHz.
- No redundancy.

DSB Vs 2SB Mixer

- DSB Mixer requires half the amount of hardware but the signal at correlator output is reduced by a factor of √2.
- DSB Mixer configuration employs 2 LNAs Vs 4 LNAs for 2SB receiver.

Complex Visibility over a baseline

$$|\mathcal{V}| \propto |U_{ground}| \cdot |U_{satellite}|$$



$$\frac{U_{DSB}}{U_{2SB}} = \frac{1}{\sqrt{2}}$$

DSB receiver power output has signal content of both sidebands.

Noise Considerations

$$\mathcal{R} = \sqrt{\frac{T_{Ag} T_{As}}{T_{Sg} T_{Ss}}} \cdot \sqrt{\frac{\Delta\nu_{IF}}{\Delta\nu_{LF}}}$$

Write $\boldsymbol{\alpha = \frac{T_{DSB}}{T_{2SB}}}$

T_{Ag} = Ant. Temp. of ground-based Rx
T_{As} = Ant. Temp. of space-borne Rx
T_{Sg} = System Temp. of ground-based Rx
T_{Ss} = System Temp. of space-borne Rx
$\Delta\nu_{IF}$ = Processed IF bandwidth
$\Delta\nu_{LF}$ = Correlator output bandwidth
$\mathcal{R}$ = **Signal-to-noise @ correlator output**

For a given $\Delta\nu_{IF}$, ratio of SNR @ correlator output between 2SB & DSB receivers

$$\mathcal{R}_{2SB-DSB} = \frac{\mathcal{R}_{2SB}}{\mathcal{R}_{DSB}} = 2\sqrt{\alpha}$$

α		$\mathcal{R}_{2SB-DSB}$
0.40	Typical 2SB Rx	1.26
0.45	Good 2SB Rx	1.34
0.50	Ideal 2SB Rx	1.41

Equation adapted from (6.43) Thompson, Moran & Swenson Jr., *Interferometry and Synthesis in Radio Astronomy*, 3rd Ed., Springer, p. 226, 2017.

DSB Vs 2SB: Comparing Different Correlation Schemes

	Relative Data Rate	Relative SNR	
		α =0.50	α =0.45
2SB (space) – 2SB (ground) 2 bit x 2 bit correlation	1.0	1.0	1.0
DSB (space) – 2SB (ground) 2 bit x 2 bit correlation	0.5	0.707	0.745
2SB (space) – 2SB (ground) 1 bit x 2 bit correlation	0.5	0.85	0.85
DSB (space) – 2SB (ground) 1 bit x 2 bit correlation	0.25	0.602	0.634

Dual Pol DSB Receiver with 4-12 GHz IF, sampled at 1 bit at Nyquist rate = 32 Gbit/sec.

wSMA SIS Mixer

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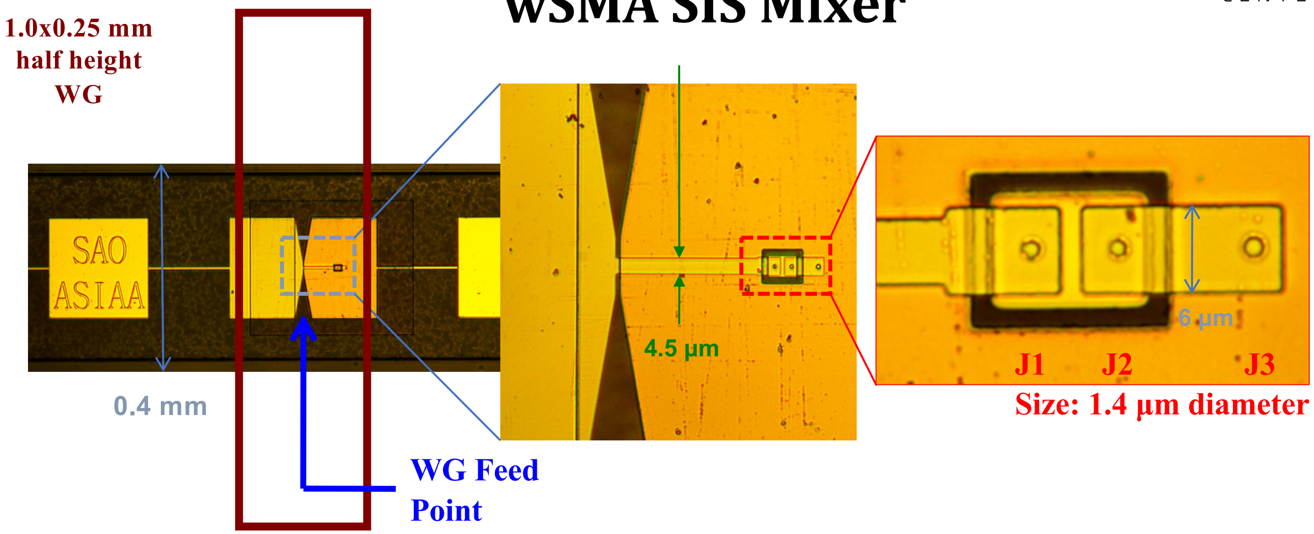
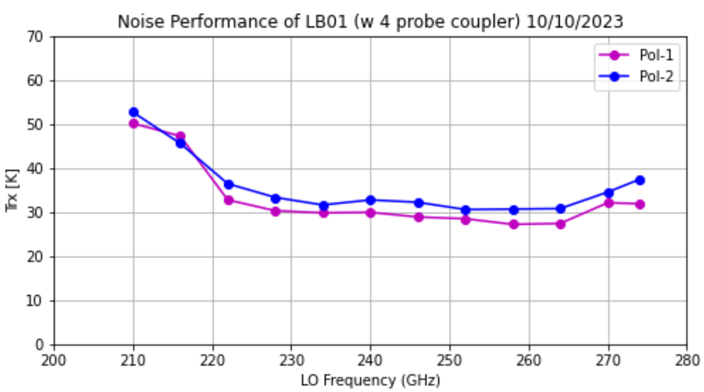


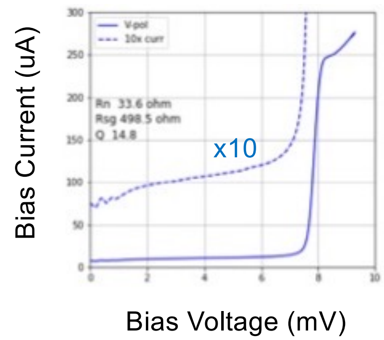


	Rx-A (Low Band)	Rx-B (High Band)
Junction Diameter	1.4 µm	1.3 µm
Target R_n-A	22 Ω - µm^2	16 Ω - µm^2
Critical Current Density	8 – 9 kA/cm^2	12 – 13 kA/cm^2
Expected R_n	30 - 40 Ω	~ 35 Ω
Chip dimensions	0.11 x 0.44 x 4 mm	0.082 x 0.33 x 3.6 mm

Wish List for BHEX SIS Receiver

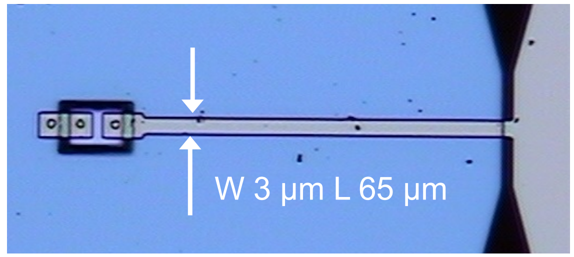
- Higher Critical Current Density 15 kA/cm^2 (R_NA~15 Ω-µm^2) – will open up possibility of wider band design.
- Low Leakage at 4.5 K ($Q > 15$) --- Ensures high conversion efficiency.
- SMA uses 3 junction series array Vs NAOJ's twin parallel junction design
- No vacuum window – wSMA vacuum window incurs ~2% loss, adds ~6 K of noise.
- Low loss optical diplexer – commercial dichroic can be lossy. Targets 2 - 3% insertion loss at 270 GHz. Optics cooled to 200 K or less (?)

SIS I-V Curve

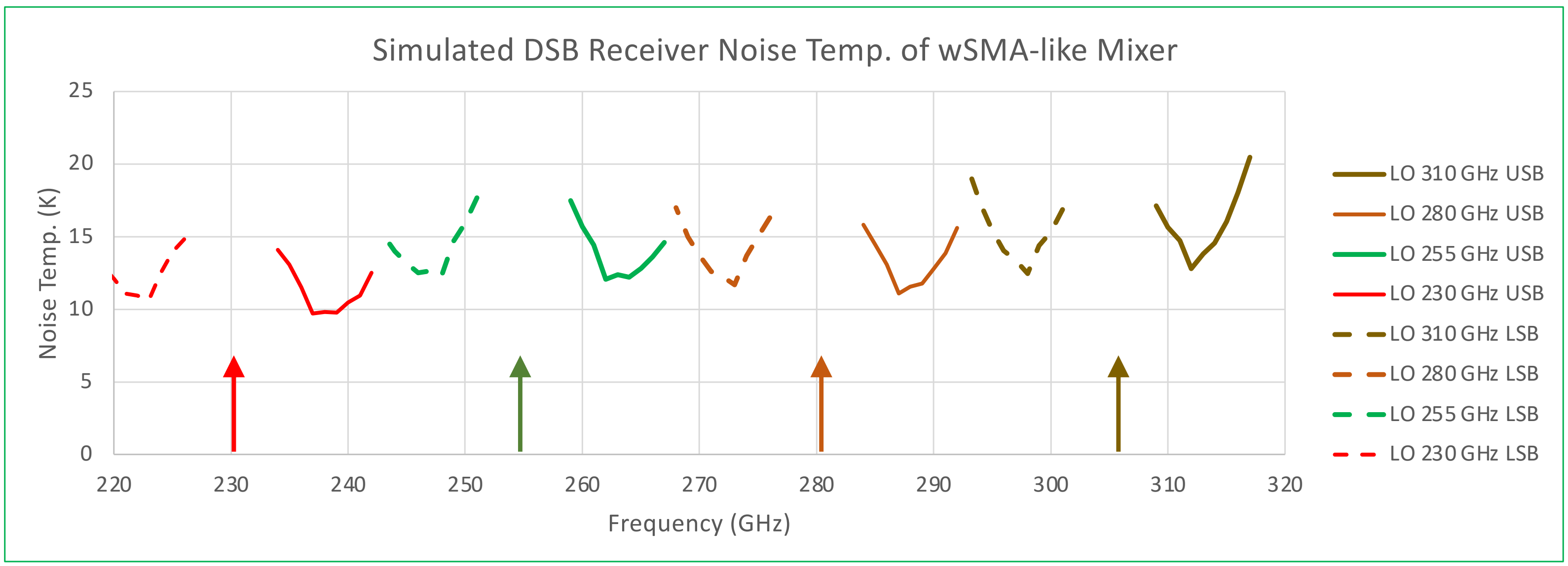


What if we scale a wSMA Mixer to BHEX Frequency Range?

$R_N A = 15\ \Omega\text{ - }\mu m^2$
3 x Dia1.4 µm Device
$C_J = 90$ fF/µm
Q = 15



$\omega C_j R_N \sim 2.4$
40 % BW is possible
wSMA is tuned for higher IF



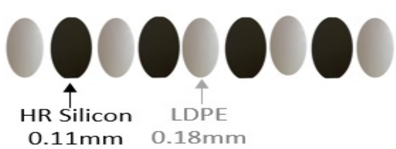
C.-Y. E. Tong, P.K. Grimes, and L. Zeng, “Noise wave modeling of an SIS mixer and its IF circuit using Tucker’s Quantum Theory of mixing,” *IEEE Trans. Appl. Supercond.,* vol. 29, no. 5, 1501105, Aug. 2019. Doi: 10.1109/TSAC.2019.2899844

Optical Diplexer

Commercial “dichroic”: multi-layer printed periodic structures

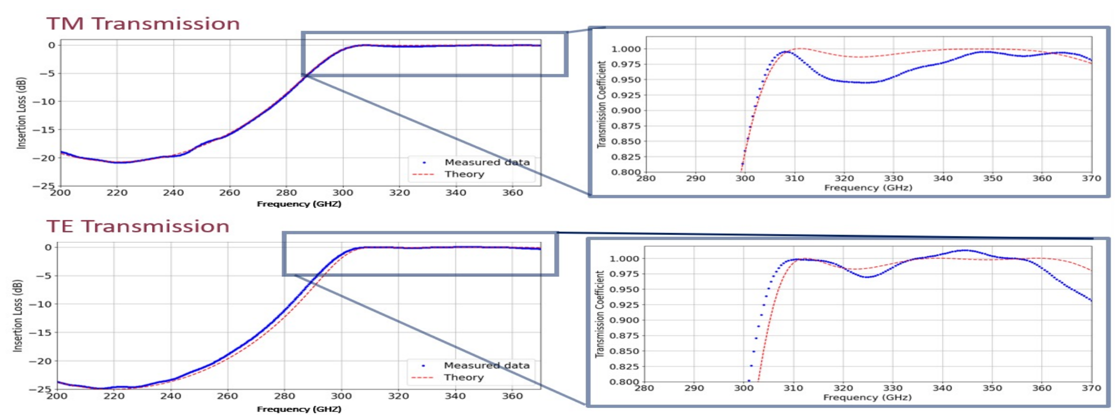
- Max incident angle 22.5°
- Losses: 5 – 8 %
- 5% loss @ 300 K = 15 K added noise:

- We are developing a new type of optical diplexer based on an optical stack built around HR silicon disks.
- A 230/345 GHz diplexer has been designed and tested.
- Incident angle 30 . Measured loss 3% @ 350 GHz.
- 100/300 GHz diplexer has designed.
- Can we cool this diplexer to lower temperature (?)



Transmission Band:
- centered at 350 GHz

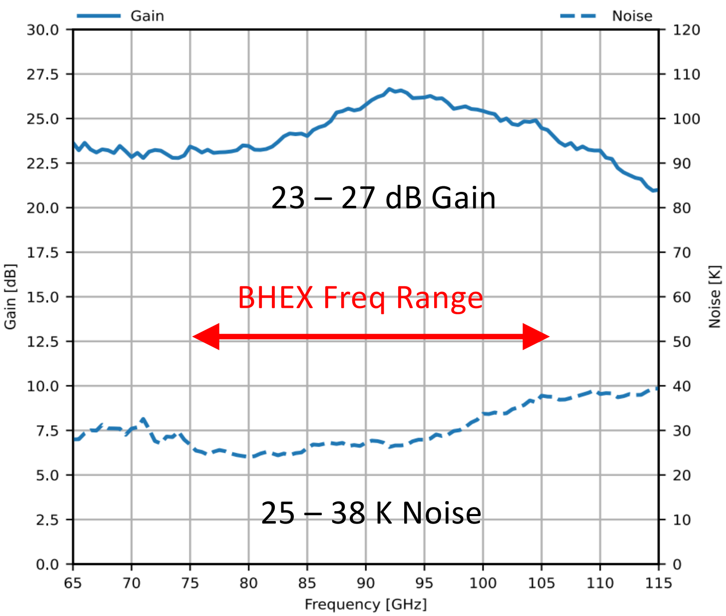
Reflection Band:
- centered at 220 GHz



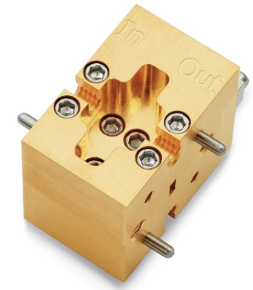
Carter, Tong, Zeng, Grimes & Kimberk, “A low-loss optical dipexer for millimeter and submillimeter radio astronomy,” presented at SPIE Yokohama, June 2024.

Rx-L: 90 GHz HEMT Receiver

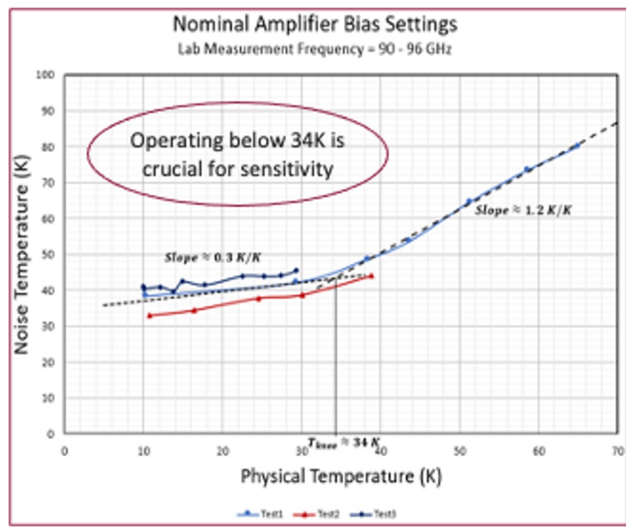
Measured data, Tamb=4 K s/n 310Z 2024



Tong, Carter & Zeng, “An 86/115 GHz sidecar receiver addition to the ngEHT receiver for OVRO & LMT,” presented at !SSTT2024, Charlottesville VA, April 2024.



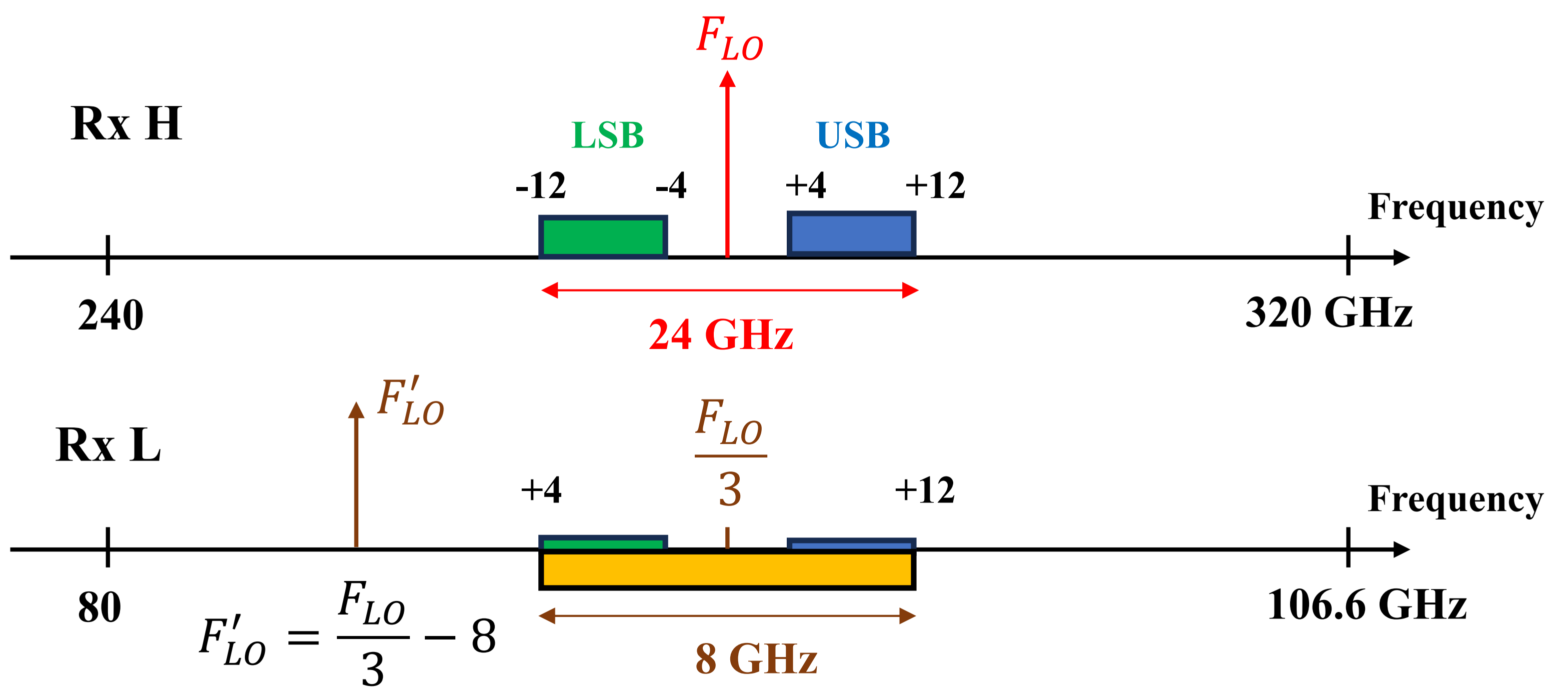
- Model LNF-LNC65_115WB made by Low Noise Factory (Sweden).
- Used as 2nd stage in ALMA2+3
- Max-Planck’s LNA has slightly lower noise.
- 2 Stages will be used with isolator in between
- Nominal DC power: 10 mW per stage



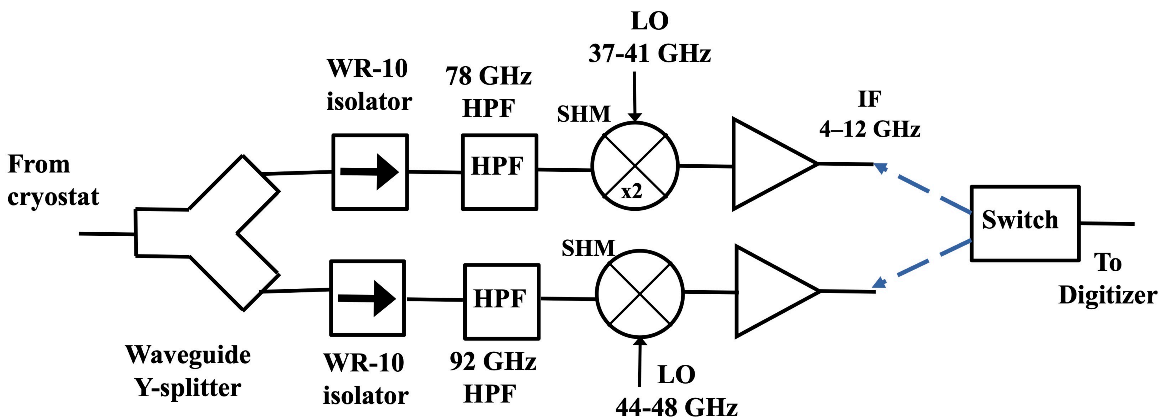
Noise penalty of ~5 K when operated at 20 K

Operation Frequency Scheme of BHEX Receiver

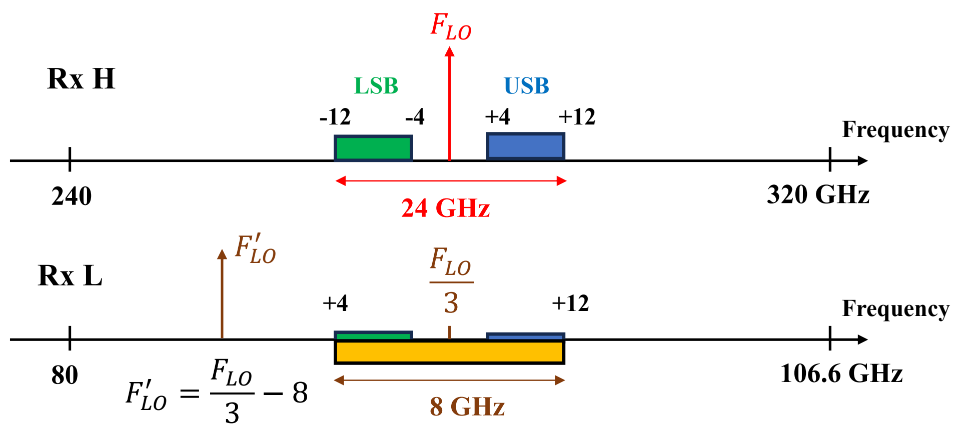
Rx-L will be operated at 1/3 the frequency of Rx-H to allow easy implementation of Frequency Phase Transfer Scheme.



Down-Converter for Rx-L

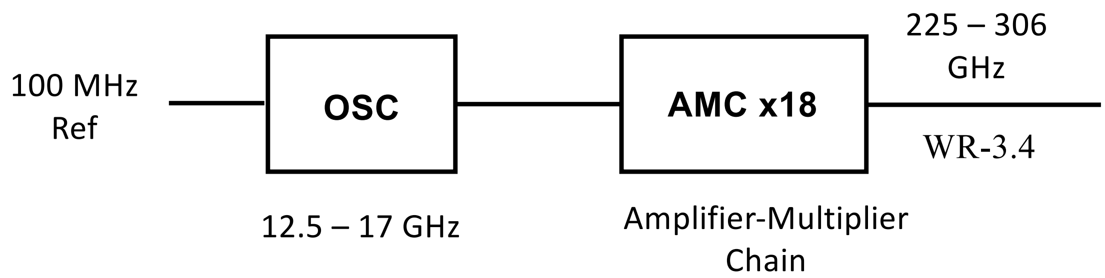


- Operates at Ambient Temp of space-craft.
- ~40 dB of gain in cryostat. Noise contribution is small.



- Second Harmonic Mixer used relaxing LO complexity.
- A waveguide HPF is used to cut off LSB of mixer
- Signal is split into 2 frequency streams: 78 – 92 GHz and 92 – 106 GHz.

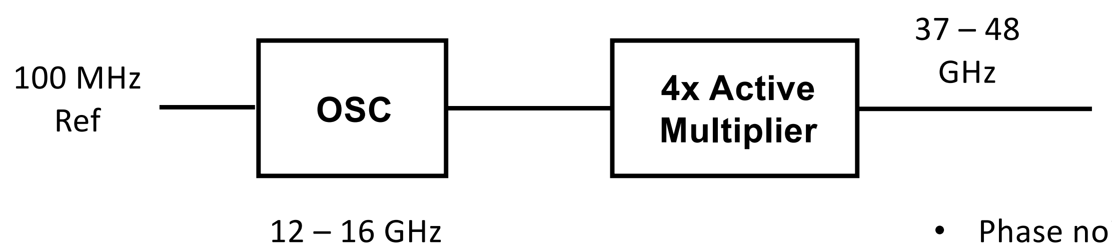
Rx-H Local Oscillator



Send into cryostat via over-moded SS WR-10 waveguide (~10 dB loss)

Required LO drive for 3-junction SIS mixer: 0.5 μW
2-pol + 20 dB coupler + WG loss → 1 mW

Rx-L Local Oscillator



Required LO power
+15 dBm (30 mW)

- Phase noise spec of microwave oscillator (?)
- OSC can be a tunable synthesizer or an array of DROs.

Status & Challenges for BHEX Receiver Development

- A receiver team has been formed: SAO + U-Arizona.
- Talking with NAOJ on mixer fabrication.
- Talked with Virginia Diodes for LO and potentially 90 GHz down-converter.

- Need to define Antenna interface – establish simple analytical model to constrain optics.
- Cal unit – an orphan?
- To work out a Receiver layout, subjected to geometry of cryocooler.
- Tone injector – only preliminary concepts so far.
- Can we tap on the space-craft cooling system to cool a radiation shield and optics. (200 K?)
- We will need a lab test cryostat for testing purpose. What level of similarities and capabilities?
- Optics diplexer – current SAO design works at ambient temperature only. Cryogenic cooled diplexer is under development.
- Phase noise specifications of base synthesizer.