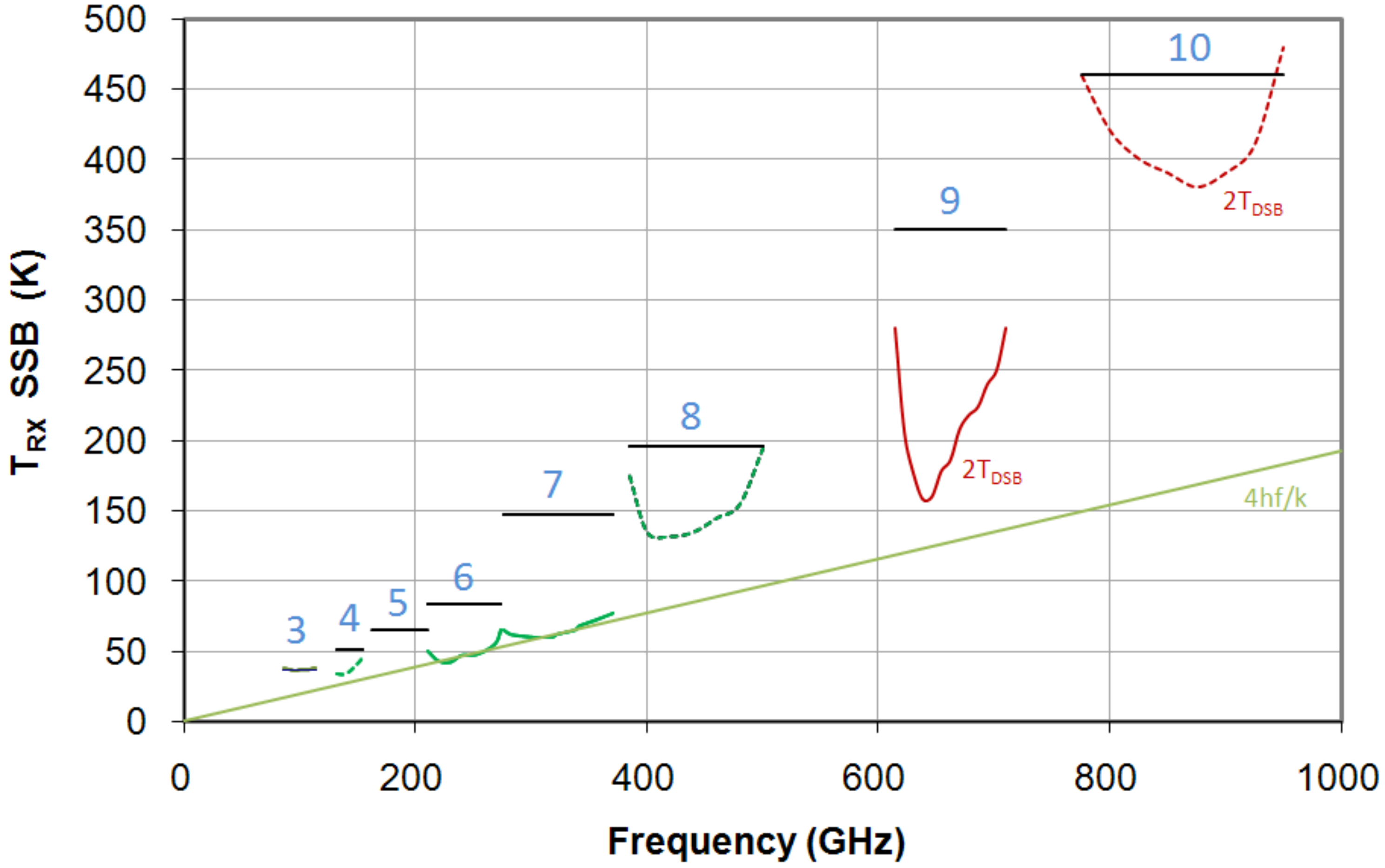
ALMA in the Coming Decade: A Development Workshop – March 21-22, 2011
NRAO, Charlottesville, VA

Receiver Development for ALMA from 300 GHz to 1+ THz

A. R. Kerr
21 March 2011

Current ALMA receiver sensitivity



What limits SIS receiver performance at high frequencies?

SIS junction characteristics

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Circuit theory bandwidth limits

RF: For a capacitive device:
Bode limit.
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Conductor loss

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  Normal metals – waveguides.
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Input optics loss

- IR filter at 80 K.
- Vacuum window at 300 K.

LO sideband noise

- Rejected by balanced design.

Material and Junction Characteristics – 1

Critical temperature T_C:		
	Nb	~ 9 K
	NbTiN	~ 15 K (cold deposited)
	NbTiN	~ 17 K (hot deposited)

Energy gap at T = 0:

Theoretical $(\Delta_1 + \Delta_2)/e = 3.52 k_B T_C / e$ [1, p. 72]

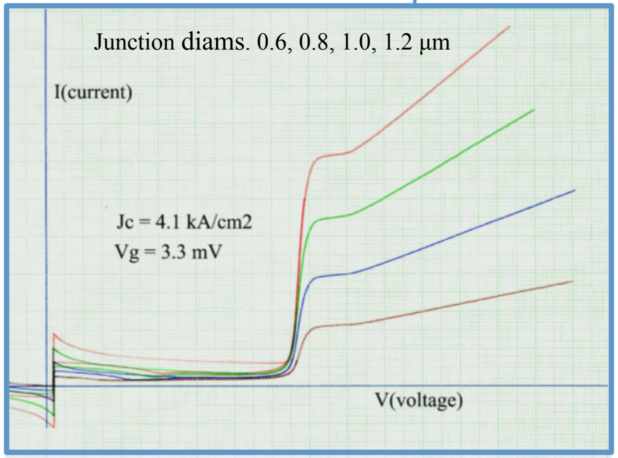
Nb//Nb	2.73 mV
Nb//NbTiN	3.64 mV
NbTiN//NbTiN	4.55 mV (hot deposited)

Experimental $(\Delta_1 + \Delta_2)/e$:

Nb//Nb	2.80 mV typical
Nb//NbTiN	3.27 mV measured to date
NbTiN//NbTiN	???

Energy gap frequency: $F_g = (\Delta_1 + \Delta_2)/h$ [1, p. 129]

Nb//Nb	660 GHz
Nb//NbTiN	880 GHz – measured 790 GHz to date
NbTiN//NbTiN	1.10 THz – ???



Ref.: A. W. Lichtenberger, 2007

[1] T. van Duzer and C.W. Turner, "Principles of superconductive devices and circuits," second ed. New York, Prentice Hall, 1999.

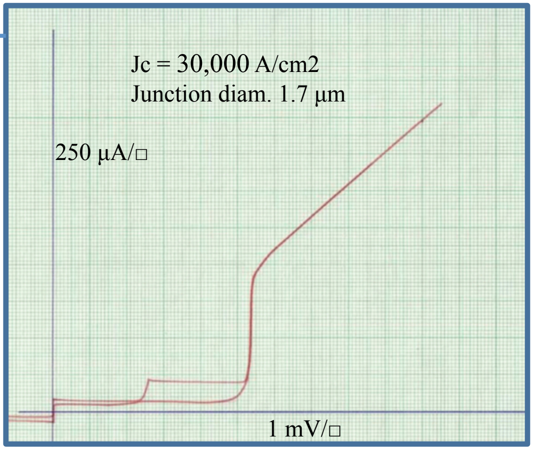
Material and Junction Characteristics – 2

$R_N I_C$: $R_N I_C = (\pi/4e)(\Delta_1(T) + \Delta_2(T)) \tanh\{(\Delta_1(T) + \Delta_2(T))/4kT\}$ [1, p. 162]

Nb//Nb	2.14 mV	cf. 1.8 mV typically measured
Nb//NbTiN	2.50 mV	
NbTiN//NbTiN	3.57 mV	

Critical current density J_C :

Nb/Al-AlOx/Nb	≤ 10,000 A/cm^2	
Nb/Al-AlN/Nb	≤ 30,000 A/cm^2	
Nb/Al-AlN/NbTiN	≤ 30,000 A/cm^2	(to date 5,000)
NbTiN/ Al-AlN/NbTiN	≤ 30,000 A/cm^2	(not yet demonstrated)



Ref.: A. W. Lichtenberger, 2007

Specific capacitance C_S:

Depends on J_C and tunnel barrier material.

Lea's empirical formula [2] for Al_2O_3 and AlN barriers:

$C_S = -18.1 + 24.9 * \log_{10}(J_C)$ $fF/\mu m^2$ – typ. 75-90 $fF/\mu m^2$

London penetration depth λ_L:

Nb	85 nm [2]
NbTiN	280 nm [3]

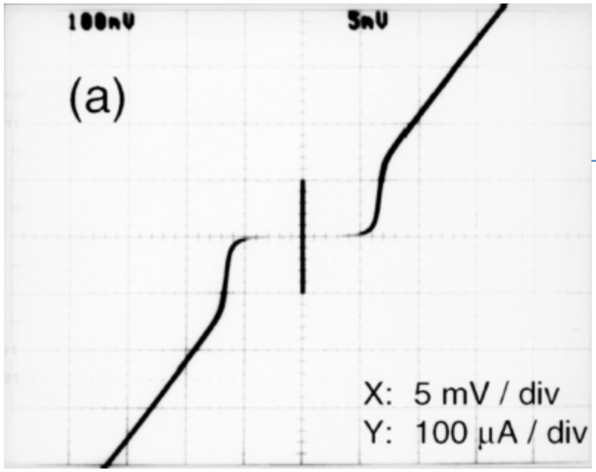
[1] T. van Duzer and C.W. Turner, "Principles of superconductive devices and circuits," second ed. New York, Prentice Hall, 1999.
[2] D. M. Lea, A. W. Lichtenberger, A. R. Kerr, S.-K. Pan, and R. F. Bradley, "On-wafer resonant structures for penetration depth and specific capacitance measurements of Nb/Al-Al2O3/Nb trilayer films," Applied Superconductivity Conference, 1994.
[3] M. Cyberey, R. Weikle and A. Lichtenberger, "On-wafer penetration depth measurements of superconducting films," Int. Symp. Space Tech., Oxford, UK, April 2010.

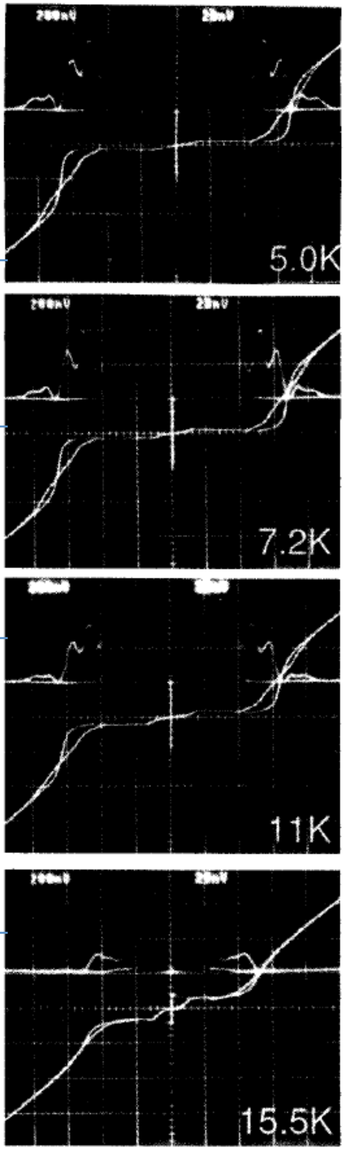
Material and Junction Characteristics – 3

Other superconducting materials:

● Pb	$T_C = 7$ K	
● Nb	$T_C = 9$ K	
● NbTiN	$T_C = 15$ K	
● BKBO (Ba(1-x)K(x)BiO3)	$T_C = 34$ K	isotropic
● MgB_2	$T_C = 39$ K	dual energy gaps
● Nb_3Ge	$T_C = 23$ K	
● Other A15 (V_3Si, V_3Ga, Nb_3Sn)	$T_C \approx 20$ K	

SIS mixer with BKBO grain-boundary junction





References: Y. Wada, T. Takami, K. Kuroda and T. Ozeki, "Significant Improvement in Ba1-xKxBiO3 Grain Boundary Junctions on MgO Bicrystal Substrates by Minimal BaBiO 3 Sputtering," Jpn. J. Appl. Phys. vol. 37, pp. L725-L727, 1998.
T. Takami, Y. Wada, K. Kuroda, T. Ozeki, and K. Hamanaka, "Quasiparticle Mixing in Ba-K-Bi-0 Grain Boundary Junctions," IEEE Trans. Applied Superconductivity, vol. 9, no. 2, June 1999.

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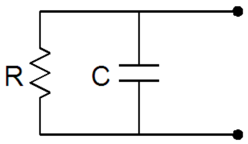
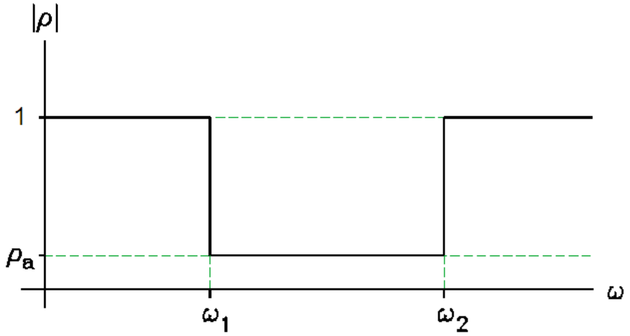
Bandwidth Limits for SIS Mixers

Bode bandwidth limit for an RC circuit

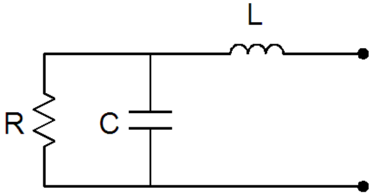


$$\int_0^\infty \ln\left|\frac{1}{\rho(\omega)}\right| d\omega \le \frac{\pi}{RC}$$



$$\ln\left(\frac{\pi}{\rho_{a,\min}}\right) = \frac{\pi}{RC\left(\omega_2 - \omega_1\right)}$$

SIS mixer with series inductance



Two cases:

(i) If L < L_B, the bandwidth is limited only by C and the Bode limit [7] applies.

(ii) If L > L_B, the bandwidth is limited by L and C. Then the Fano limit [8] applies.

For an SIS junction, can not do LP → BP transformation because it is not possible to connect an inductor directly in parallel with the junction capacitance. Then the modified Bode-Fano theory of [9] is used:

ρ_a is given by $K = \frac{2}{\pi}\ln\left(\frac{1}{\rho_{a,\min}}\right)$, where K is the real solution of

$$K^3 - \frac{6}{bB_C}K^2 + \left[\frac{12}{b^2}\left(1 + \frac{1}{{B_C}^2}\right)\right]K - \frac{24}{b^3 X_L {B_C}^2} = 0$$

with $b = 2\frac{\omega_2 - \omega_1}{\omega_2 + \omega_1}$, $B_C = \omega_0 C,$ and $X_L = \omega_0 L.$

[7] H. W. Bode, "Network Analysis and Feedback Amplifier Design," New York: Van Nostrand, 1945.

[8] R. M. Fano, "Theoretical Limitations on the Broadband Matching of Arbitrary Impedances," J. Franklin Inst., vol. 249, pp. 57-83 and 139-155, Jan. and Feb. 1950.

[9] A. R. Kerr, "Some fundamental and practical limits on broadband matching to capacitive devices, and the implications for SIS mixer design," IEEE Trans. Microwave Theory Tech., vol. MTT-43, no. 1, pp. 2-13, Jan. 1995

Series Arrays of SIS Junctions

Advantages of a series array of N junctions

For a given impedance level the junctions can be N times larger.

Larger junctions:

- More consistent I_C and C_J
- Better I(V) quality → lower noise.
- Higher gain compression level (x N^2) → better calibration

Arrays allow higher impedance levels (x N)

- Helps reduce loss
- Allows better coupling to IF amplifier

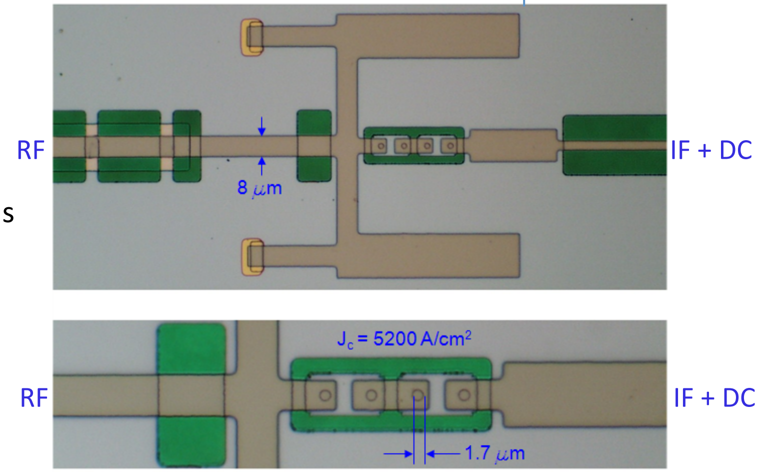
Series connection allows IF circuit to be decoupled from the RF circuit

- Wider IF bandwidth [10].

Disadvantages

Require more LO power (x N^2). Not usually a problem with modern LO sources.

(Offset by balanced mixers which require 10-20 dB *less* LO power.)



Four-junction series SIS array as in the ALMA Band 6 SIS mixers

[10] A. R. Kerr, S.-K. Pan, A. W. Lichtenberger and H. H. Huang, "A Tunerless SIS mixer for 200–280 GHz with low output capacitance and inductance," Proceedings of the Ninth International Symposium on Space Terahertz Technology, pp. 195-203, 17-19 March 1998. http://www.nrao.edu/meetings/isstt/papers/1998/1998195203.pdf

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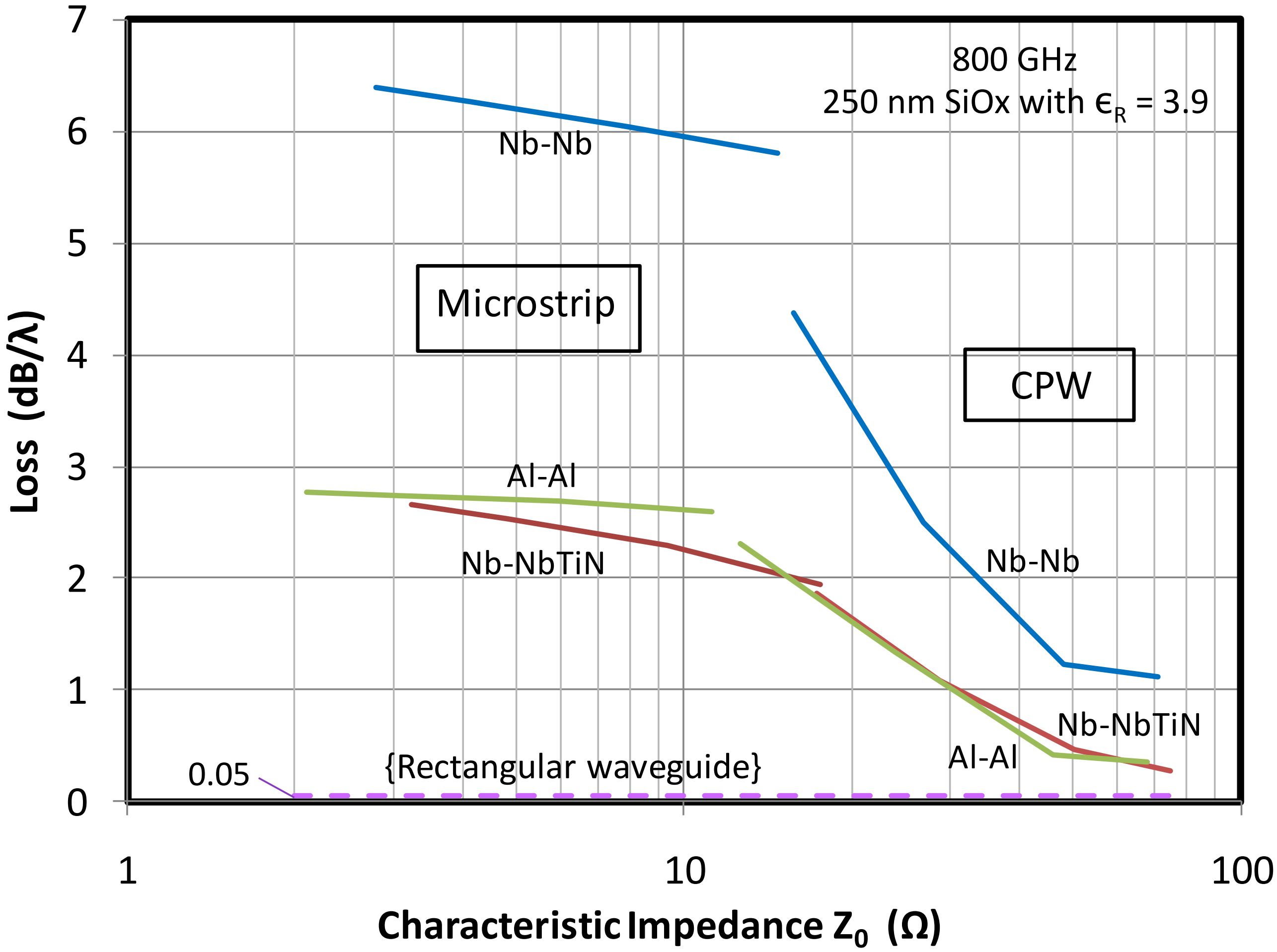
Transmission line characteristics

Example: Loss vs Z_0 for microstrip and coplanar waveguide at 800 GHz



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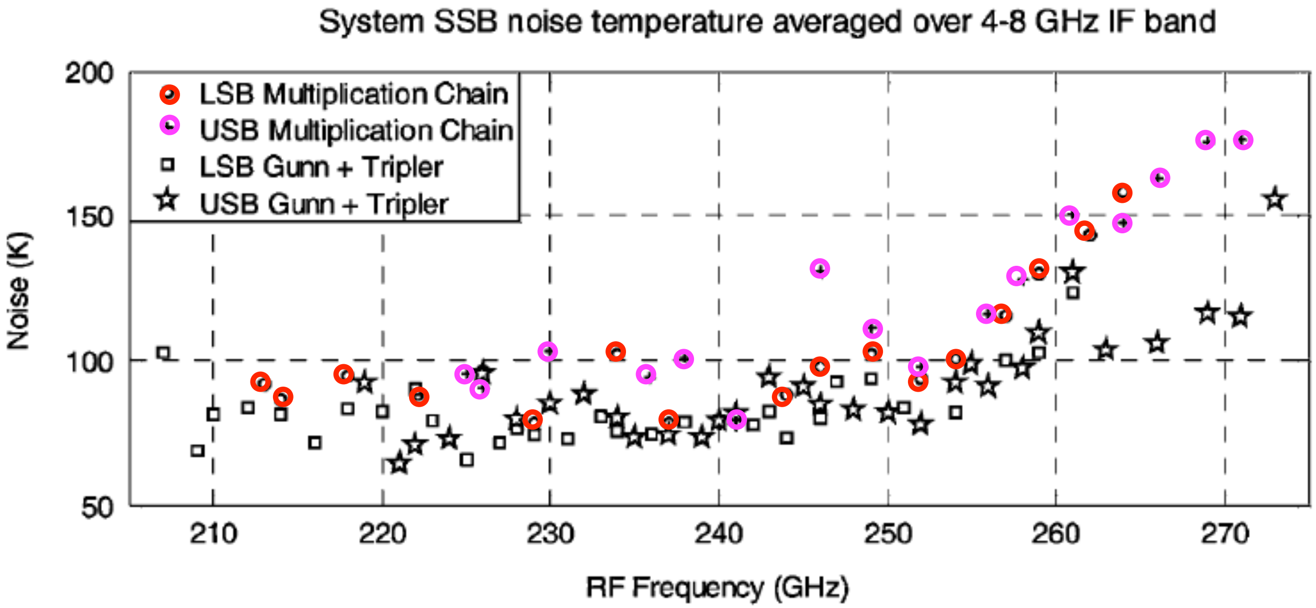
LO Sideband Noise



Reference: V. Vassilev, D. Henke, I. Lapkin, O. Nyström, R. Monje, A. Pavolotsky, and V. Belitsky, "Design and Characterization of a 211–275 GHz Sideband Separating Mixer for the APEX Telescope," IEEE Microwave and Wireless Components Letters, Vol. 18, No. 1, pp. 58-60, January 2008.

Improved sub-mm receivers for ALMA and the path to > 1 THz

- AlN barriers to replace Al_2O_3 barriers
  - – Higher J_C allows wider RF bandwidth

- Wider-band IF amplifier
  - – 5-15 GHz (?) with no IF isolator

- Balanced mixer configuration
  - – Superconducting 180° IF hybrid
    - – Rejects LO noise

- Drop-in 90° waveguide hybrid – for balanced &/or sideband separating mixers
  - – Reduced loss and greater reproducibility

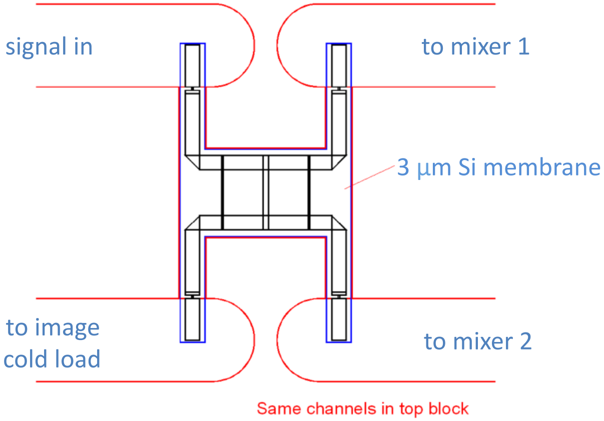
- Drop-in LO couplers
  - – Greater reproducibility

- Put mixer circuit on Si membrane with beam leads
  - – Greater reliability. Easier to fabricate and mount (higher yield)

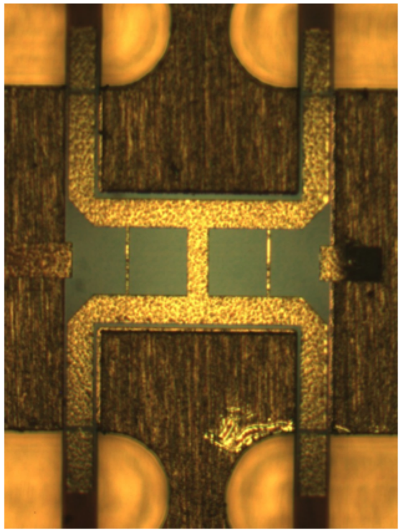
- New superconductors for Band 10 and above (?)

Some components for next-generation SIS receivers – 1

Drop-in 90° waveguide hybrid

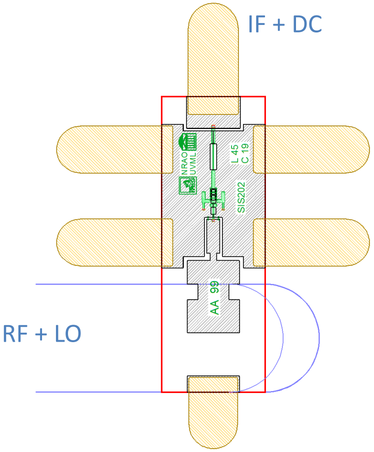


Waveguide size 250 x 125 µm for 1 THz operation



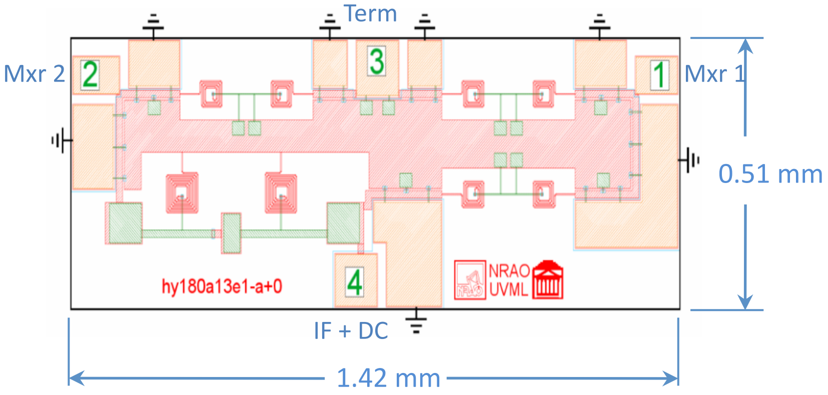
Reference: E. Bryerton & A. W. Lichtenberger, 2010

SIS mixer circuit on a 3-µm Si membrane with beam leads



Waveguide size 250 x 125 µm for 1 THz operation

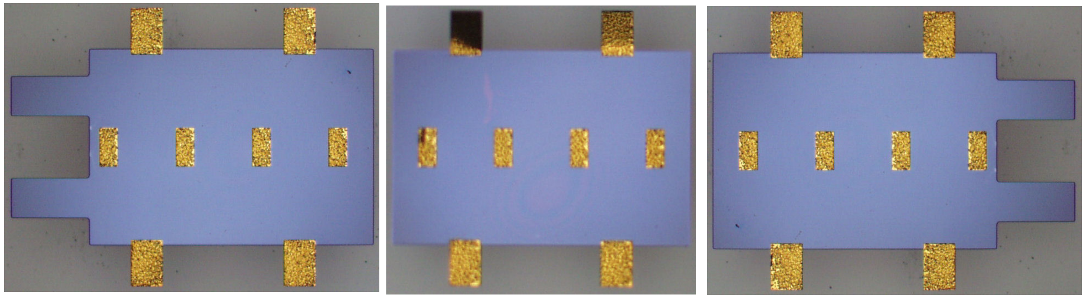
Superconducting 4-12 GHz 180°-hybrid on a quartz chip



Reference: A. R. Kerr, A. W. Lichtenberger, C. M. Lyons, E. F. Lauria, L. M. Ziurys, and M. R. Lambeth, "A Superconducting 180° IF Hybrid for Balanced SIS Mixers," Proc. 17 th Int. Symp. on Space THz Tech., Paris, pp. 29-32, May 2006.

Some components for next-generation SIS receivers – 2

Adjustable drop-in LO coupler – 10/16/20 dB



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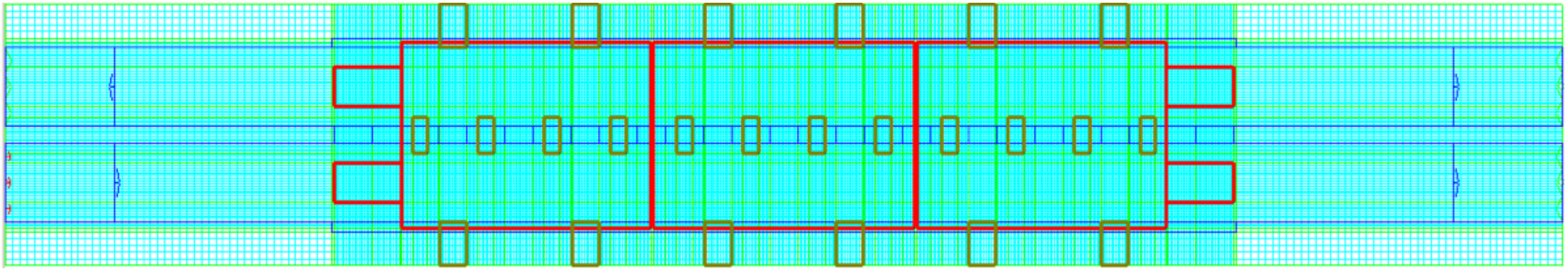
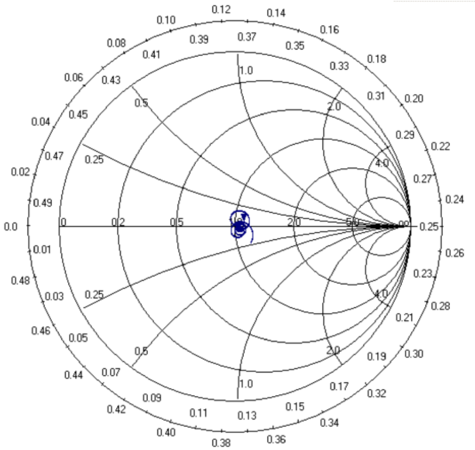
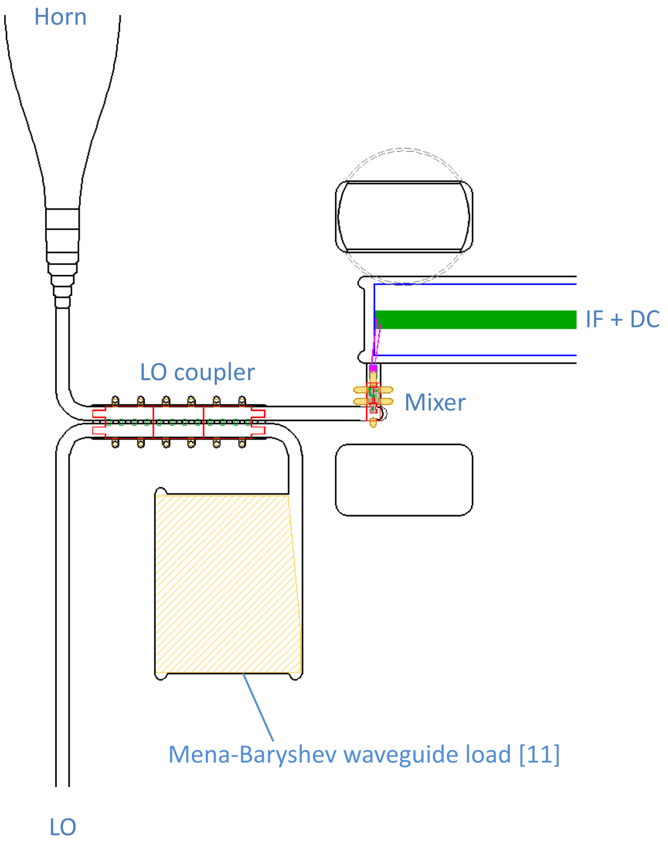


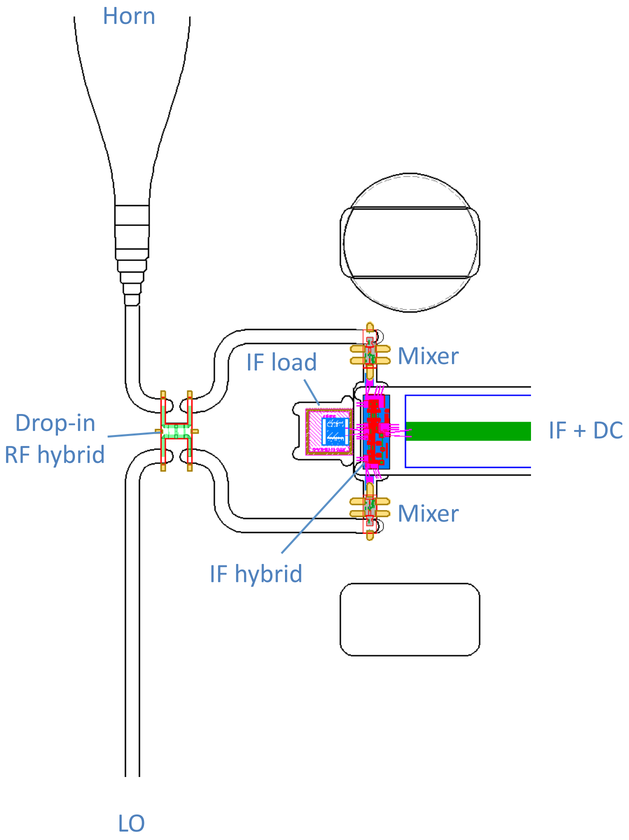


Next-generation SIS mixers – 1

Single-ended mixer



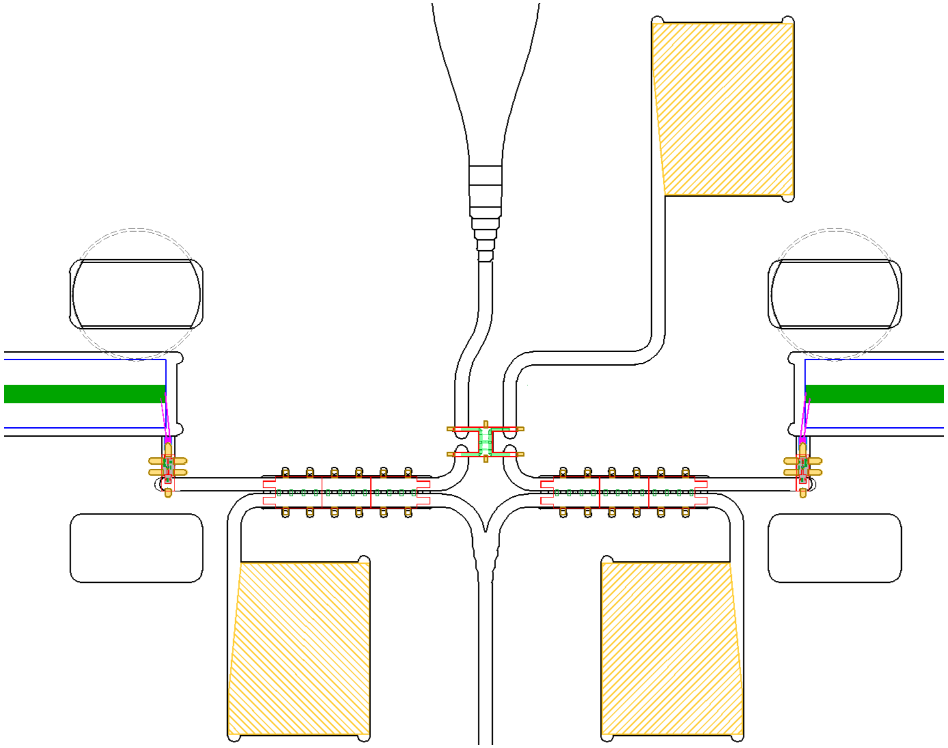
Balanced mixer



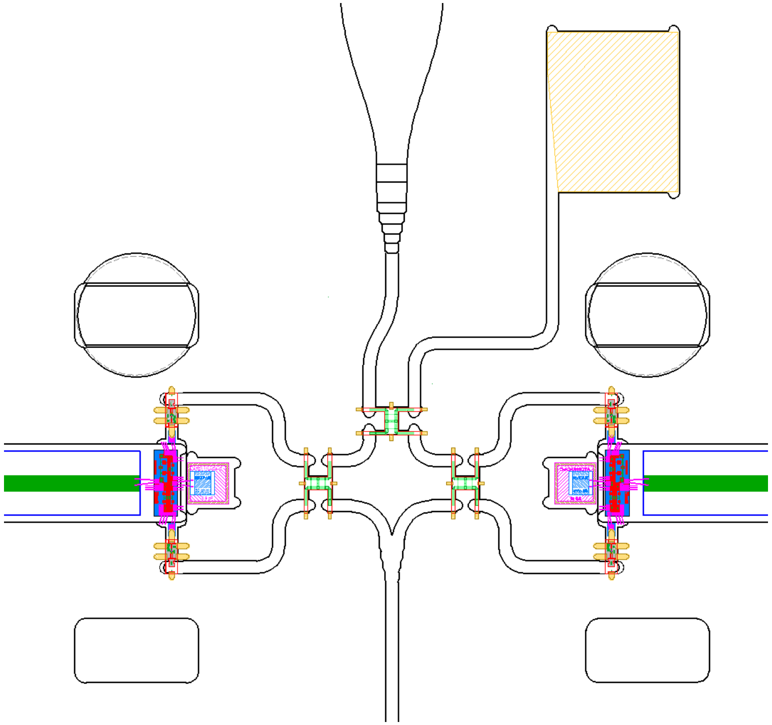
[11] F. P. Mena and A. Baryshev, "Design and Simulation of a Waveguide Load for ALMA-band 9", ALMA Memo 513, Jan 2005. http://science.nrao.edu/alma/aboutALMA/Technology/ALMA_Memo_Series/alma513/memo513.pdf

Next-generation SIS mixers – 2

Sideband-separating mixer



Balanced sideband-separating mixer



"It's just a theory, but perhaps it's their opposable thumbs that makes them crazy."

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