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National Radio Astronomy Observatory

Atacama Large Millimeter/submillimeter Array
Expanded Very Large Array
Robert C. Byrd Green Bank Telescope
Very Long Baseline Array

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National Science Foundation

Associated Universities, Inc.

A Planar OMT for the EVLA

8-12 GHz Receiver Front-End

Michael Stennes

October 1, 2009

Atacama Large Millimeter/submillimeter Array
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EVLA

Acknowledgement

The author wishes to thank Robert Simon for his help in wire-bonding the assemblies, Mike Hedrick and Dwayne Barker for the machining of OMT housings and chip carriers.

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References

[1] W. A. Tyrrell, "Hybrid circuits for microwaves, " PROC. IRE, vol. 35, pp. 1294–1306; November, 1947.

[2] J. P. Shelton, "Tandem couplers and phase shifters for multi-octave bandwidth", Microwaves, pp. 14-19, April 1965.

[3] S. B. Cohn, "Shielded Coupled-Strip Transmission Line", Trans. IRE, Vol. 3, Issue 5, October 1955.

[4] D. Bock, "Measurements of a scale-model ortho-mode transducer", BIMA memo 74, July 7, 1999.

[5] R. L. Plambeck, G. Engargiola, "Tests of a planar L-band orthomode transducer in circular waveguide", Rev. Scientific Instruments, Vol. 74, No. 3, March 2003.

[6] P. K. Grimes, et al, "Compact broadband planar orthomode transducer", Electronics Letters, Volume 43, Issue 21 Oct. 11 2007 Pages1146 - 1147

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OMT Goals

- To provide coupling to two orthogonal linear polarizations, TE11 mode in circular waveguide, diameter 2.337 cm.
- Synthesize circular polarization by combining linear polarizations in a 90-degree hybrid.
- Provide for noise cal injection.
- Implement and integrate all of these functions in a planar transmission media, in a compact form, such that will fit in the existing VLA 8.0-8.8 GHz dewar and able to be cooled by a CTI model 22 refrigerator.

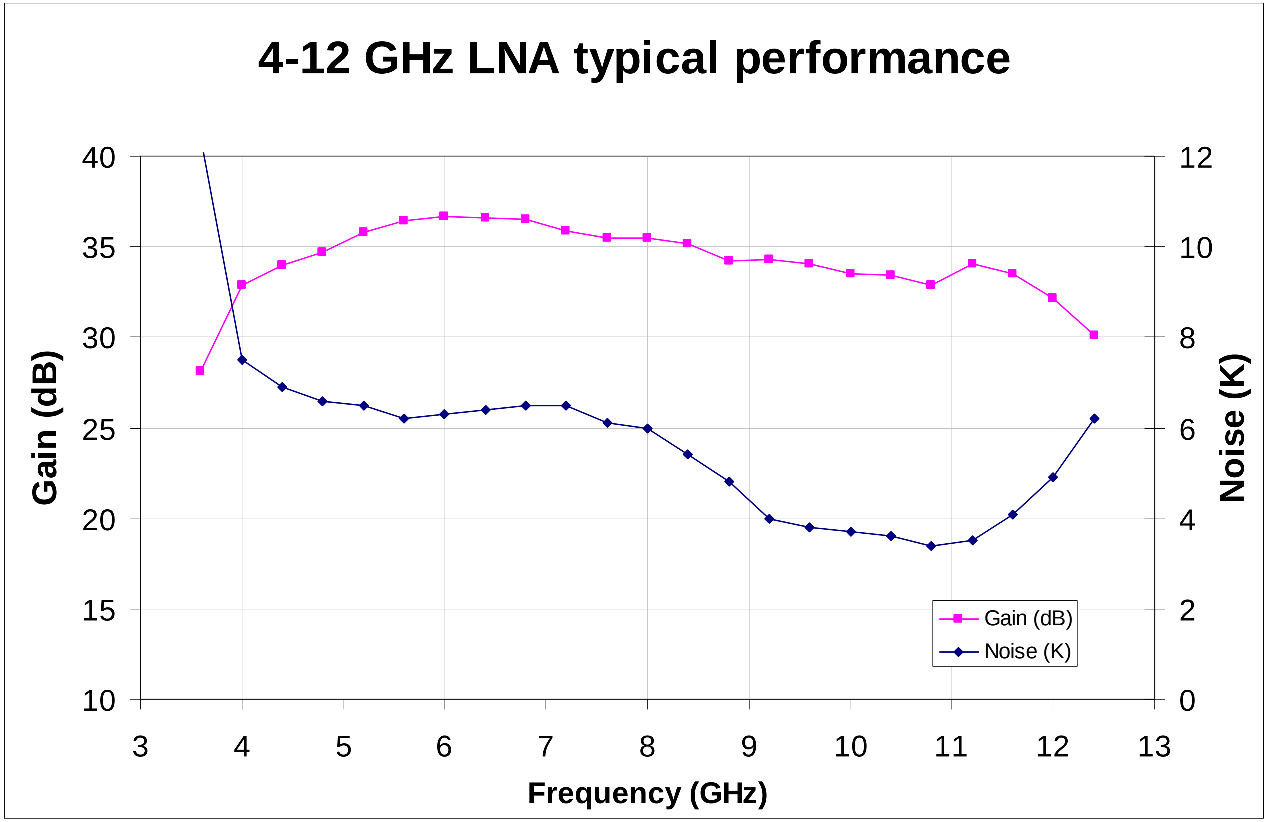
X-Band Receiver Specifications

- From EVLA Project Book

Frequency Range	8.0-12.0 GHz
Noise Temperature (including feed)	> 20 K
Circular Polarization Axial Ratio	< 1 dB
System Gain	55 dB
Output Power on Cold Sky	-30 dBm
Headroom above 1% Compression Point	> 30 dB
Dynamic Range Above “Quiet Sun” Level	> 30 dB (in Solar Mode)
Circular Polarizer	TBD

Noise Budget

- Cryogenic LNA



Receiver Noise Level Analysis

- OMT Loss = 1 dB

EVLA X-Band Receiver Level Analysis   M. J. Stennes   5/10/2008

C:\Documents and Settings\mstennes\Desktop\EVLA\Level Analysis Spreadsheet
Linear Polarization
Page 1 of 1

Note: This level analysis is for the proposed redesign of the EVLA X-band receiver, using a planar OMT

		1	2	3	4	5	6	7	8	9	10	11
	Signal	feed horn	OMT	Couplers (3)	Isolator	Amplifier	SS Coax	Isolator/filter	Amplifier	Atten	Filter	Atten
Gain (dB)		-0.10	-1.00	-0.02	-0.30	35.00	-1.00	-0.60	16.30	-3.00	-0.50	-3.00
Cum. Gain (dB)		-0.10	-1.10	-1.12	-1.42	33.58	32.58	31.98	48.28	45.28	44.78	41.78
Gain (ratio)		0.977237	0.794328	0.9954054	0.9332543	3162.2777	0.7943282	0.8709636	42.657952	0.5011872	0.8912509	0.5011872
Cum. Gain (ratio)		0.977237	0.776247	0.7726806	0.7211075	2280.3421	1811.3401	1577.6113	67297.666	33728.731	30060.763	15066.071
Noise Figure (dB)		0.103	0.056	0.001	0.016	0.065	0.371	0.619	2.400	3.074	0.516	3.074
Cum. Noise Figure (dB)		0.103	0.160	0.161	0.181	0.268	0.268	0.268	0.270	0.270	0.270	0.270
Noise Figure (ratio)		1.02	1.01	1.00	1.00	1.02	1.09	1.15	1.74	2.03	1.13	2.03
Cum. Noise Figure (ratio)		1.024096	1.037435	1.037743	1.0425305	1.063571	1.0636101	1.0636947	1.0641624	1.0641777	1.0641815	1.0642157
Noise Temp (K)		6.99	3.78	0.07	1.07	4.40	25.89	44.45	213.96	298.58	36.61	298.58
Cum. Noise Temp (K)		6.99	10.86	10.95	12.33	18.44	18.45	18.47	18.61	18.61	18.61	18.62
GkTeB (Watts)		3.77E-13	1.66E-13	3.804E-15	5.527E-14	1.344E-09	6.812E-12	2.137E-12	5.038E-10	8.26E-12	1.801E-12	2.478E-11
GkTeB (dBm)		-94.23714	-97.8053	-114.19724	-102.5755	-58.7157	-81.66735	-86.70227	-62.97724	-80.83002	-87.44514	-76.05881
Cum. GkTeB (Watts)		6.47E-13	6.79E-13	6.801E-13	6.9E-13	3.526E-09	2.808E-09	2.447E-09	1.049E-07	5.259E-08	4.687E-08	2.352E-08
Cum. GkTeB (dBm)		-91.89318	-91.6786	-91.674239	-91.61166	-54.52719	-55.51664	-56.11284	-39.79194	-42.79125	-43.29109	-46.28651
Tcal (K)	5.00											
Tcal (dBm)	-94.62	-95.69	-96.69	-96.71	-97.01	-62.01	-63.01	-63.61	-47.31	-50.31	-50.81	-53.81
Tmax (K)	310.00											
Tmax (dBm) [GkTmaxB]	-80.68	-77.77	-78.77	-78.79	-79.09	-44.09	-45.09	-45.69	-29.39	-32.39	-32.89	-35.89
Physical Temperature		300	14.6	15	15	15	100	300	300	300	300	300
Bandwidth (GHz)		4	4	4	4	7	24	4	4	4	4	12
T test (K)	10											
P1dB (dBm)						-5			16			
Signal Density (dBm/MHz)		-127.9138	-127.699	-127.69484	-127.6323	-92.97817	-99.31875	-92.13344	-75.81254	-78.81185	-79.31169	-87.07832

Commercially Available Hybrid Couplers

- Cost, Performance

90-Degree Hybrid

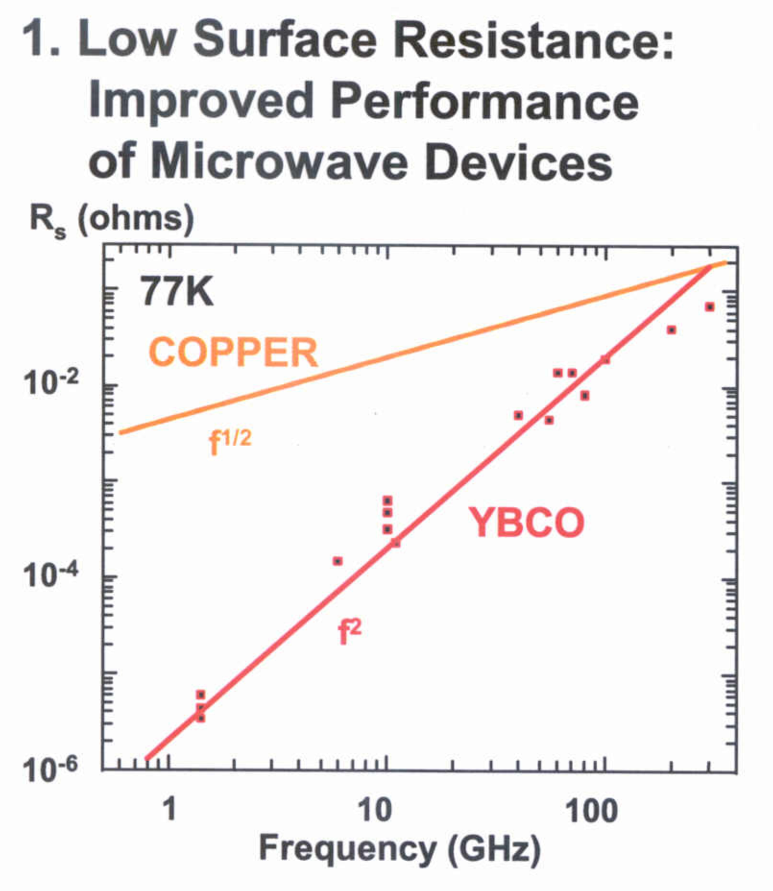
Manufacuter, Model No.	Freq. (GHz)	Ampl. Bal. (± dB)	Phase Bal. (± deg)	VSWR (x:1)	Rtn Loss (-dB)	Iso (-dB)	I.L. (-dB)	Price USD	Deliv. (weeks)
MCLI HB-6	7.0-12.4	0.5	not spec.	1.30	17.7	18	0.9	229	2
Mac Tech C7206	6.0-12.4	0.5	5.0	1.35	16.5	18		108	8
ET Indust. Q-612-90	6.0-12.4	0.5	4.0	1.35	16.5	20	0.7	425	1
Krytar 1830	2.0-18	0.4	7.0	1.35	16.5	17	1.4	875	5

180-Degree Hybrid

Manufacuter, Model No.	Freq. (GHz)	Ampl. Bal. (± dB)	Phase Bal. (± deg)	VSWR (x:1)	Rtn Loss (-dB)	Iso (-dB)	I.L. (-dB)	Price USD	Deliv. (weeks)
MCLI HJ-10	7.0-12.4	0.6	5.0	1.50	14.0	15	0.8	975	4
Miteq, Inc.	8.0-12.4	1.0	8.0	1.5	14.0	15	1.0	375	9
ET Indust. J-612-180	6.0-12.4	0.4	5.0	1.45	14.7	18	1.0	705	1
Krytar 4040124	4.0-12.4	0.4	8.0	1.6	12.7	17	0.9	745	5

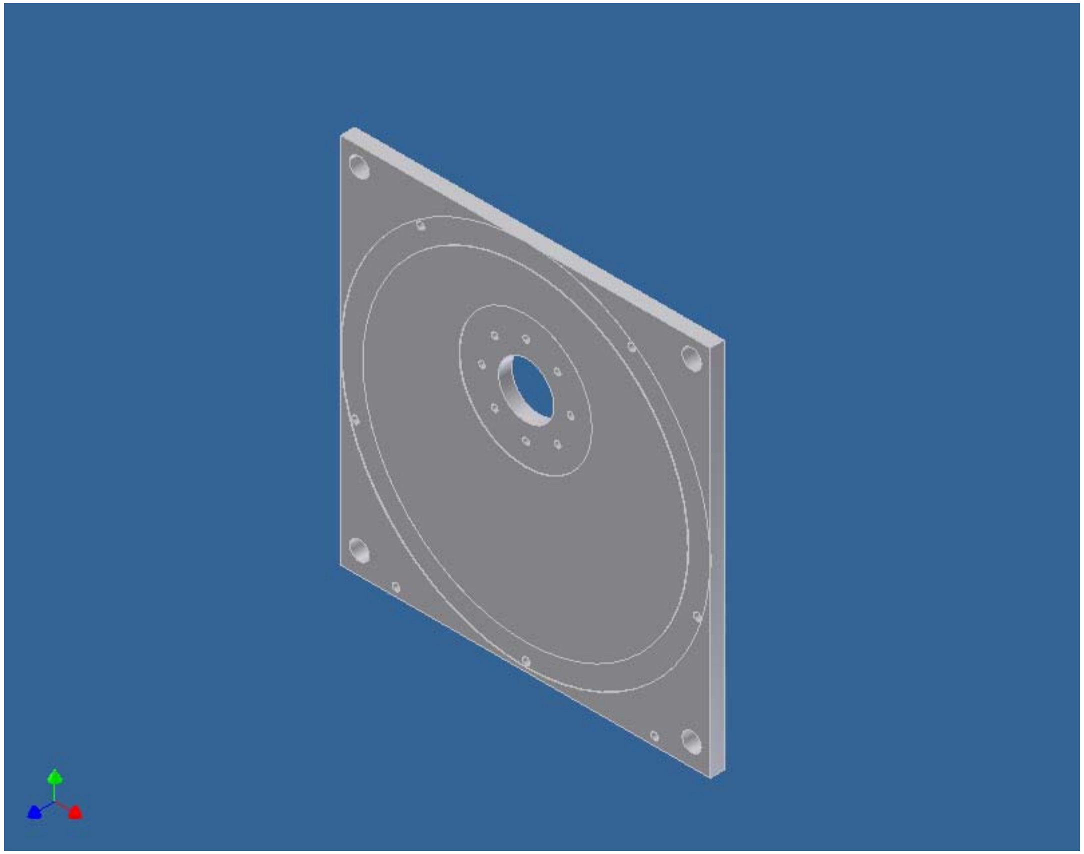
YBCO Surface Resistance on MgO

- Compare Copper & YBCO (courtesy Northrop Grumman)



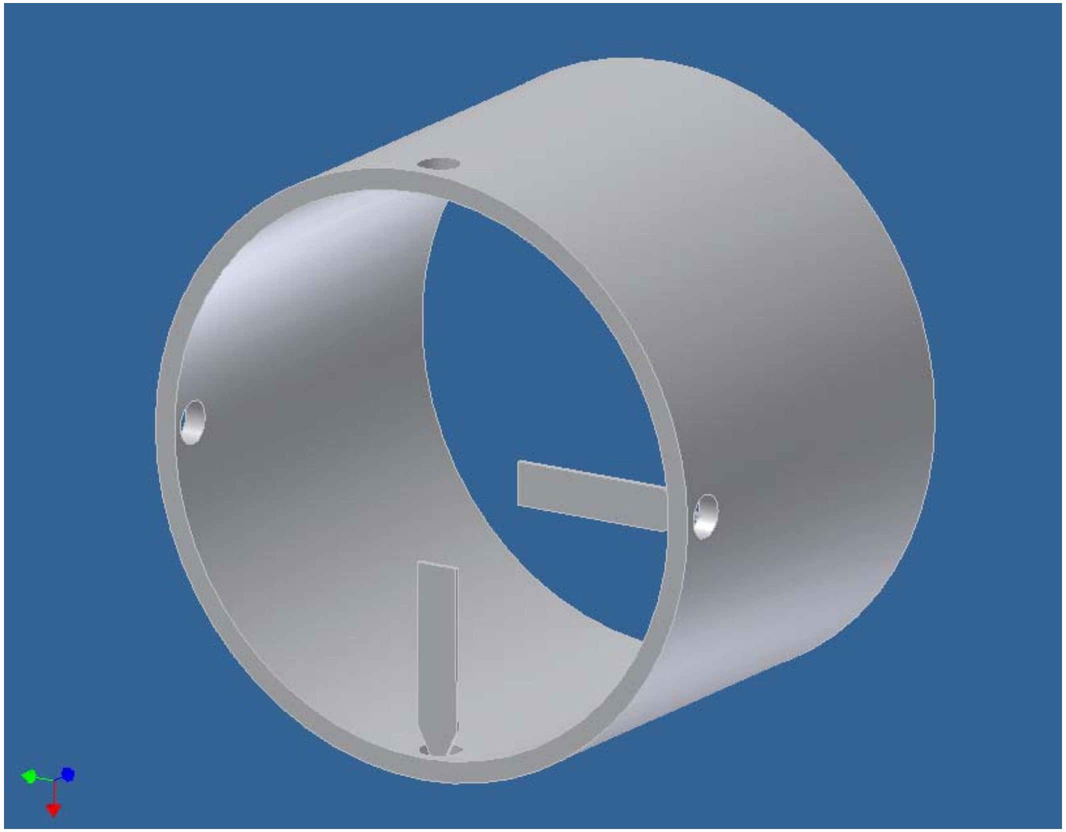
New Dewar Top Plate

- Inventor Model



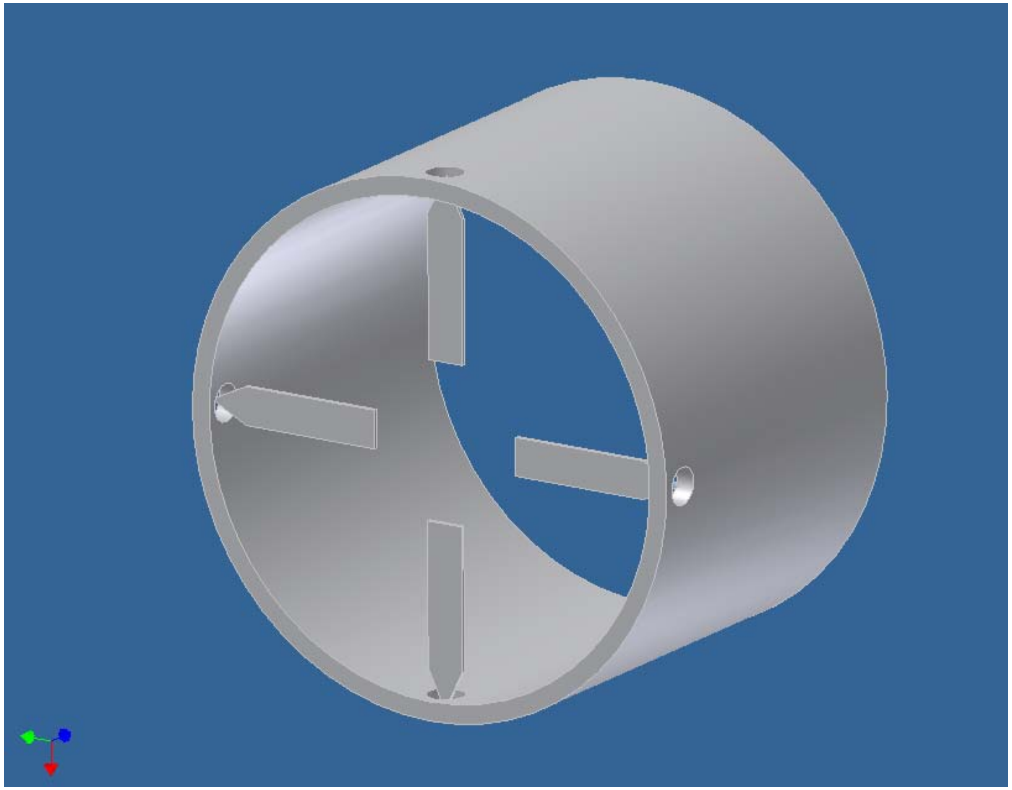
Waveguide Probe Design

- Single-ended approach does not have the required bandwidth



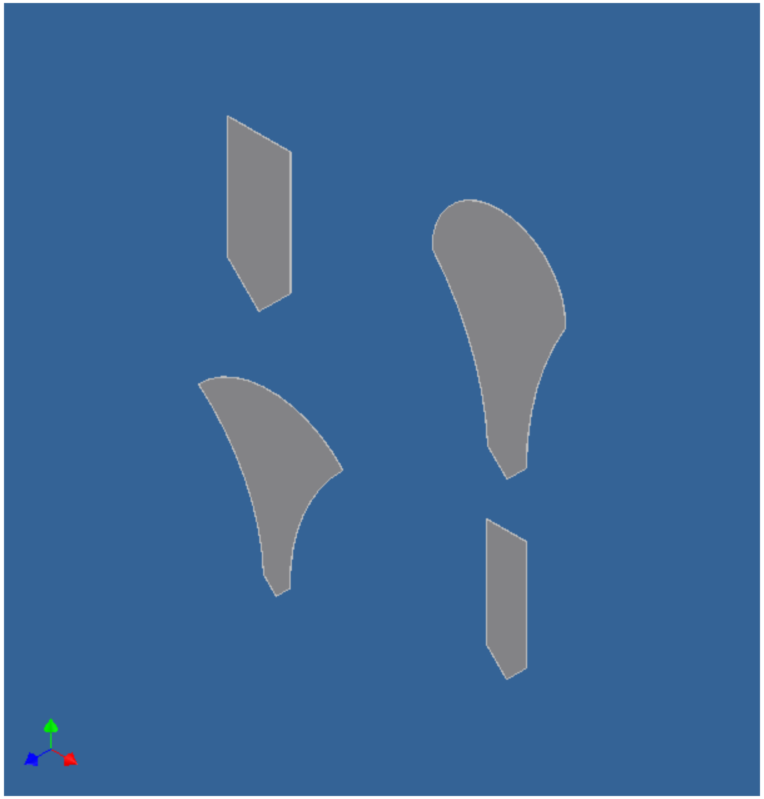
Balanced Probes

- Probes fed 180-degrees out of phase, s11 < -20 dB over 8-12 GHz



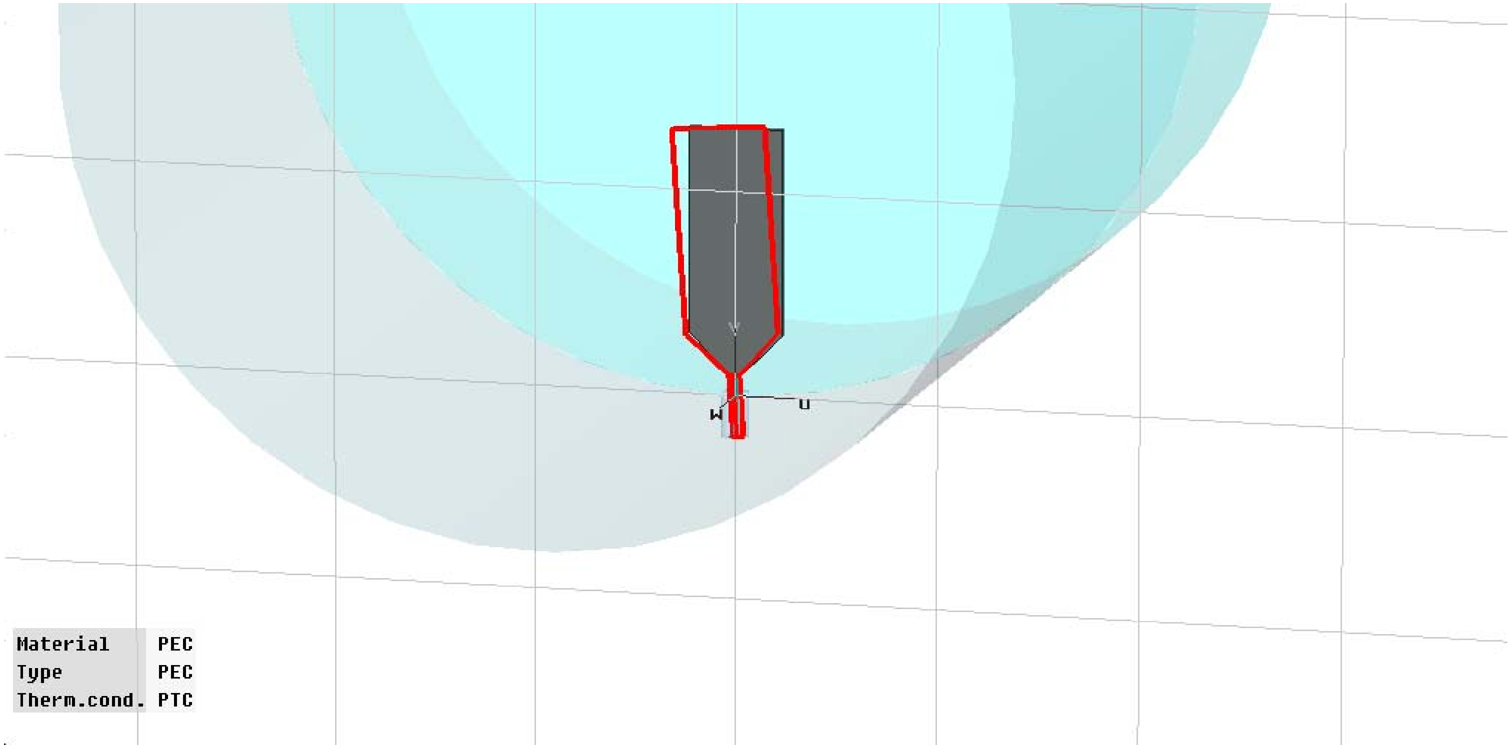
Probe Shape

- Radial, Rectangular

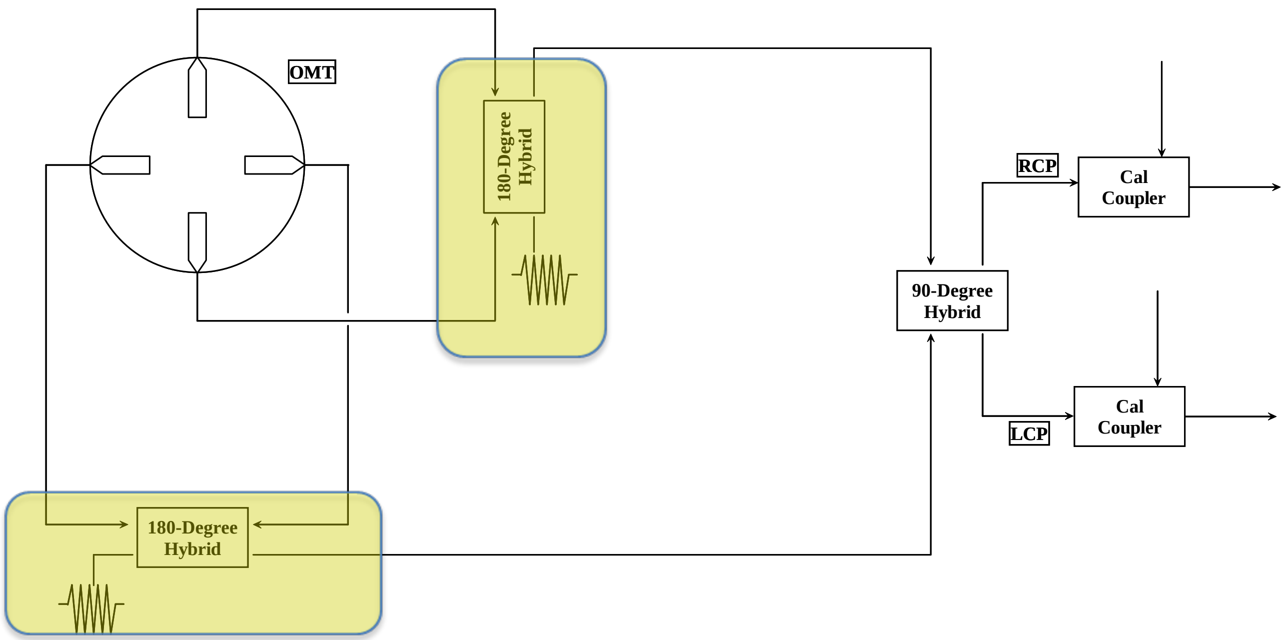


Waveguide Probe Design

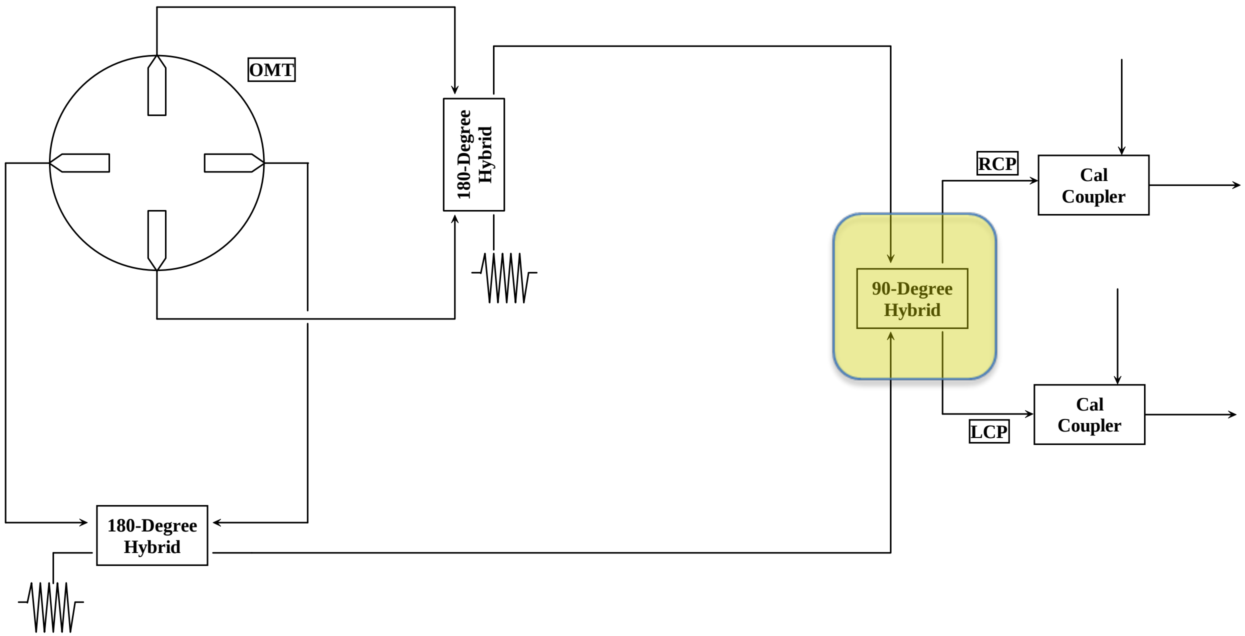
- CST Model



- Schematic

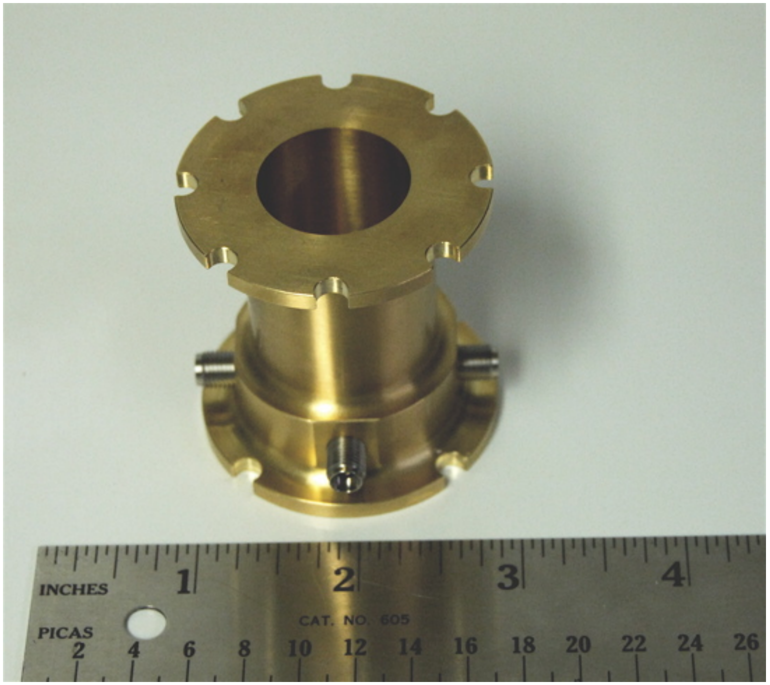

OMT
180-Degree Hybrid
180-Degree Hybrid
90-Degree Hybrid
RCP
LCP
Cal Coupler
Cal Coupler

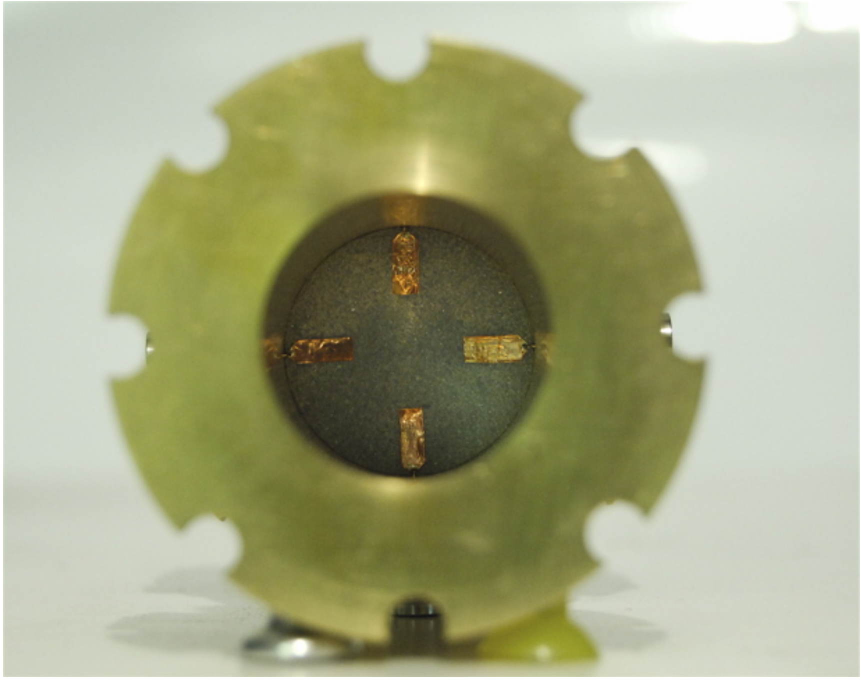
- 90Degree Hybrid



OMT Probes: Prototype

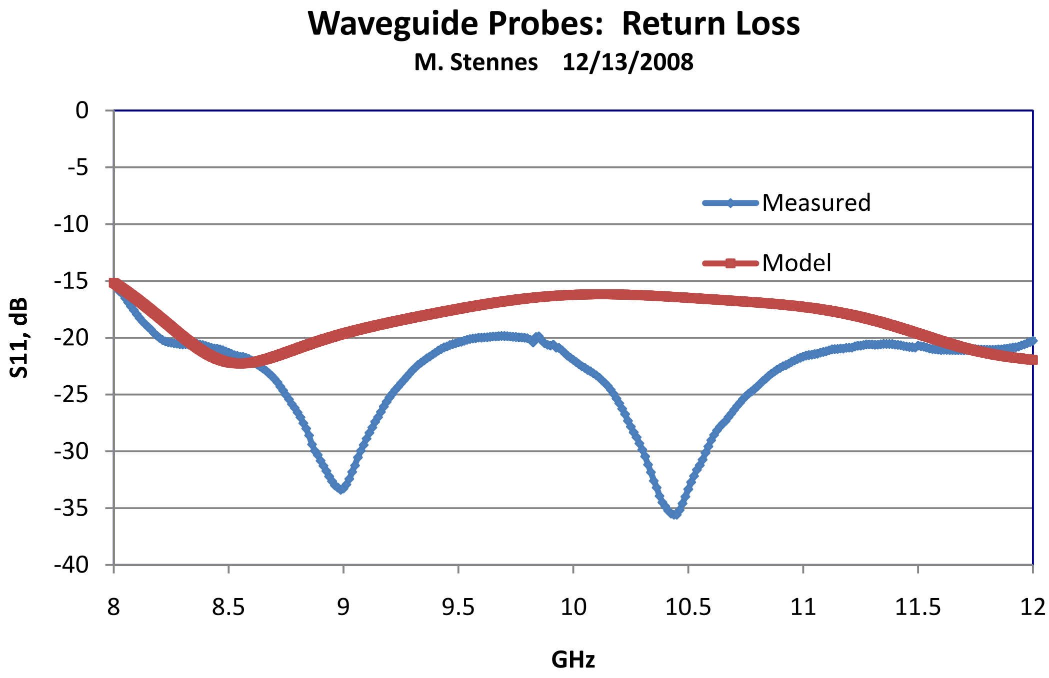
- Copper tape supported by Ecco-Foam PS-102





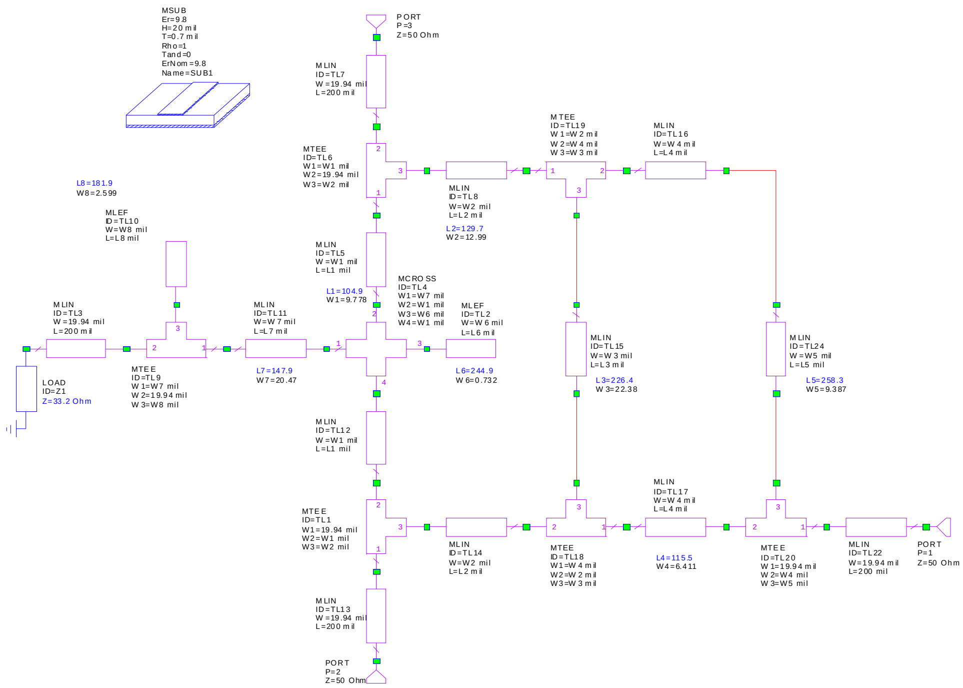
Probe Design

- Measured Return Loss & CST Prediction



180-Degree Hybrid Coupler

- Modified "Rat Race" Circuit
- MWO Linear Circuit Model



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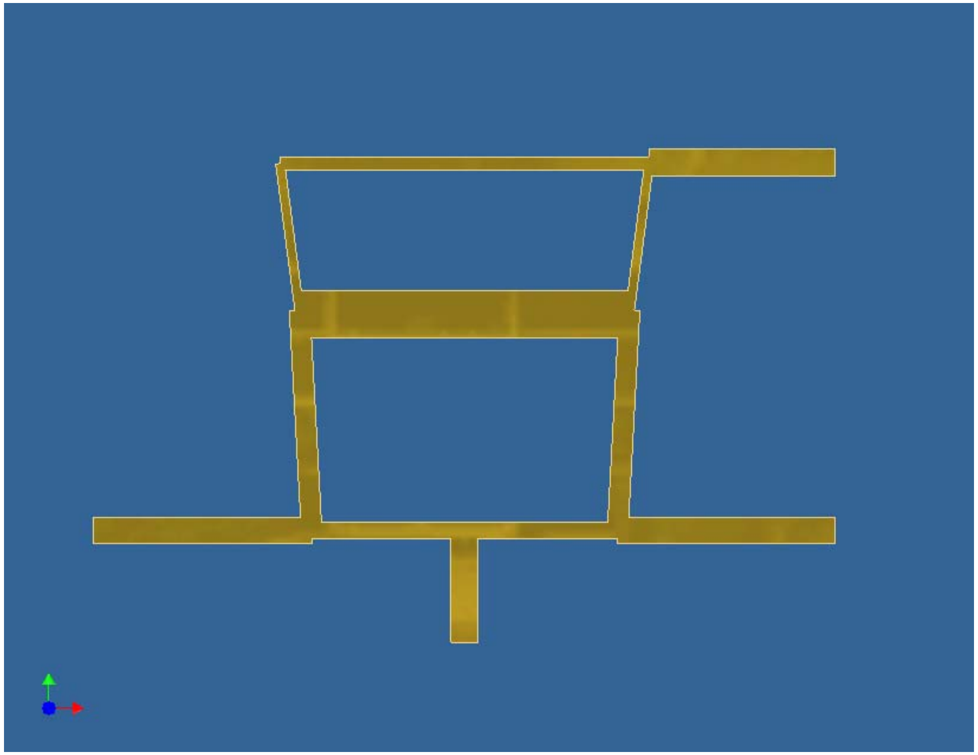
180-Degree Hybrid: Design

- 3D EM model, CST

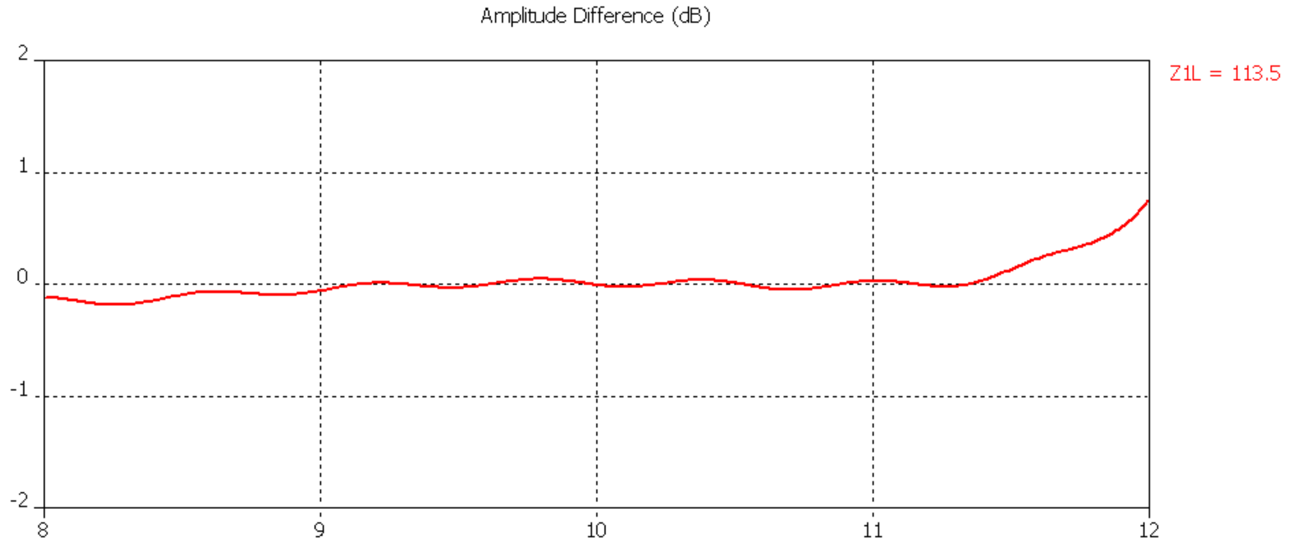


180-Degree Hybrid Coupler

- CST Model: Amplitude Balance

180-Degree Hybrid: Amplitude Balance (Model)

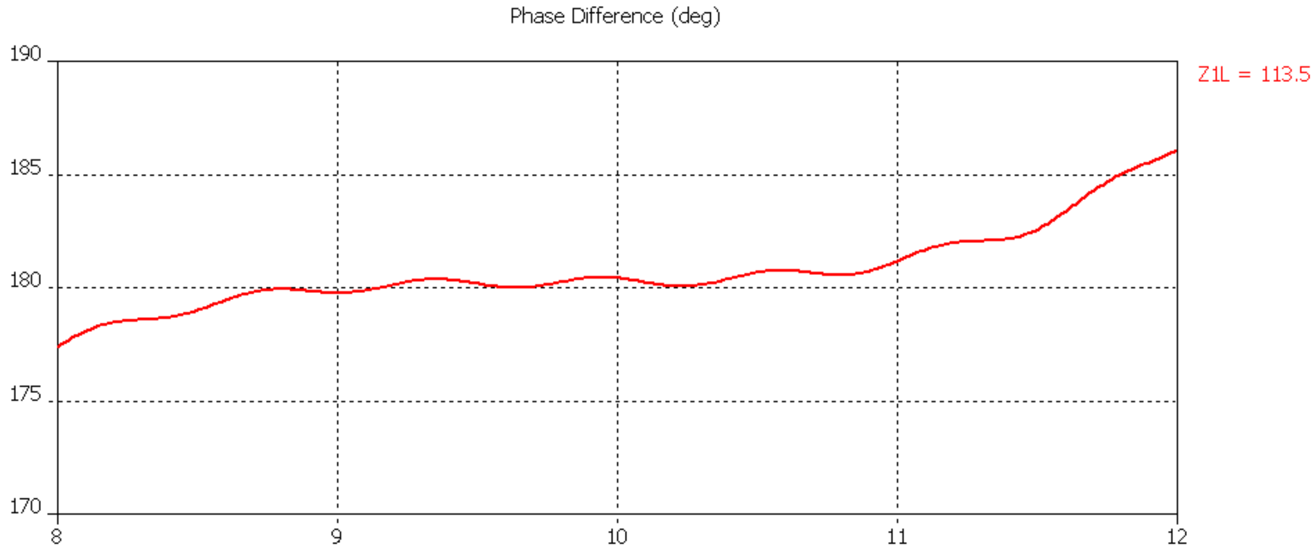
M. Stennes 1/21/2009



180- Degree Hybrid Coupler

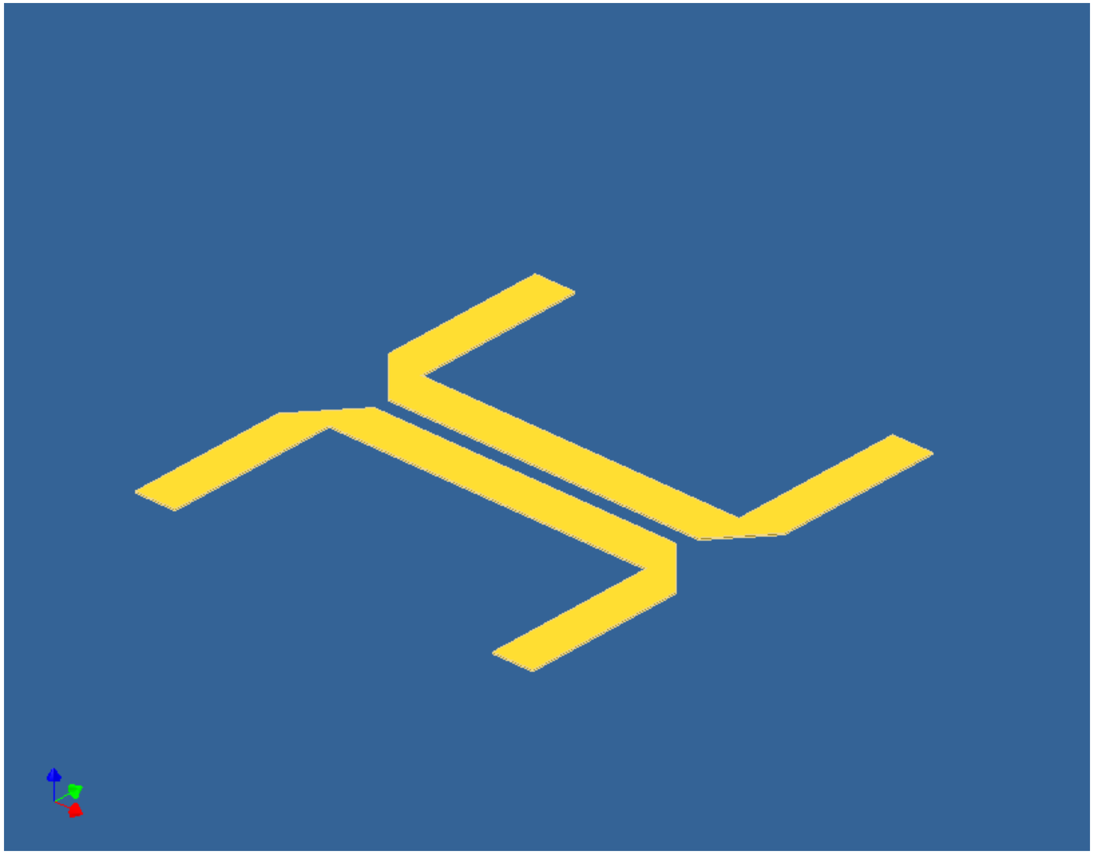
- CST Model: Phase Balance

180-Degree Hybrid: Phase Difference (Model)
M. Stennes 1/21/2009



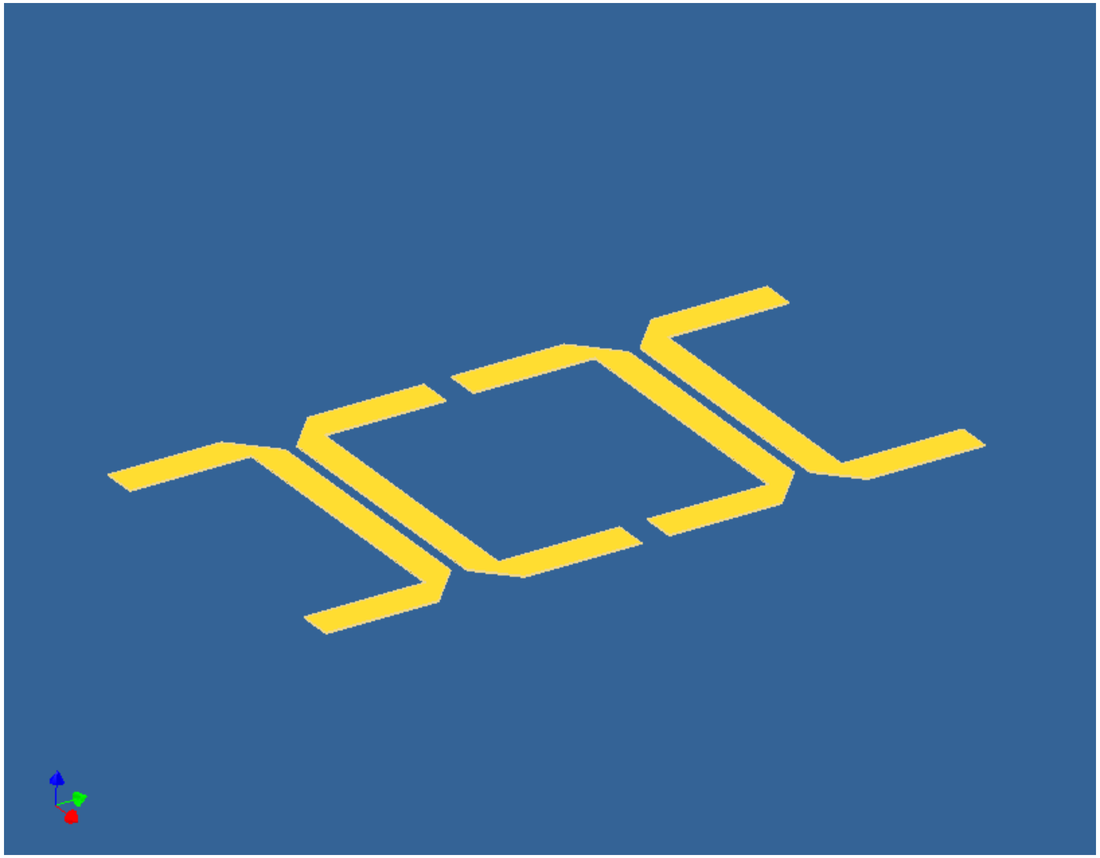
90-Degree Hybrid Design

- Backward wave coupler, $\lambda/4$ length



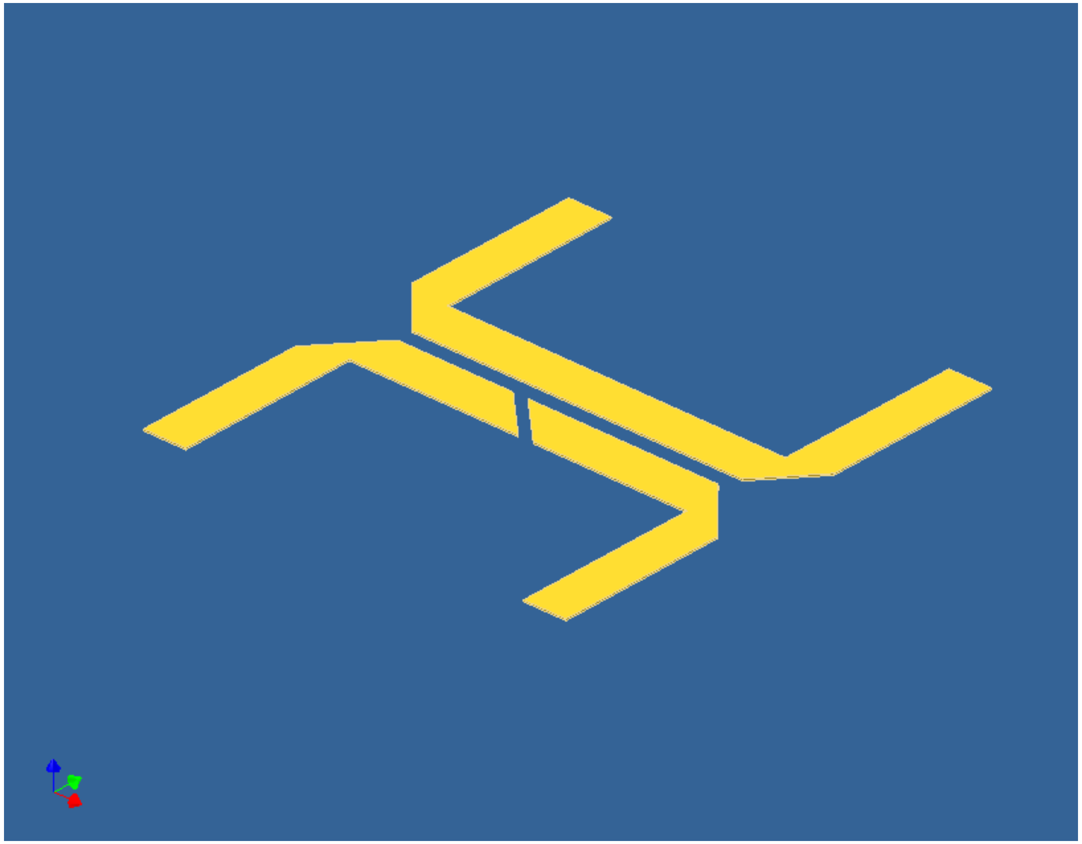
90-Degree Hybrid Coupler Design

- Tandem pair, 8.3 dB coupling



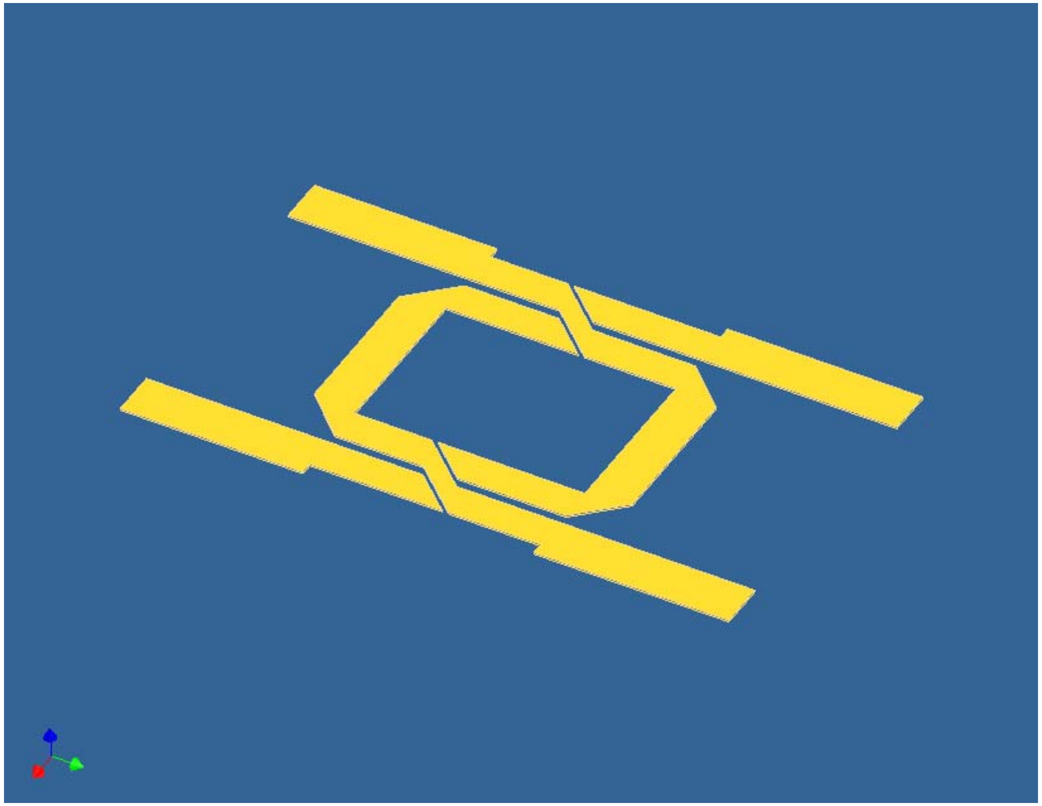
90- Degree Hybrid Coupler Design

- Cut and twist coupled lines



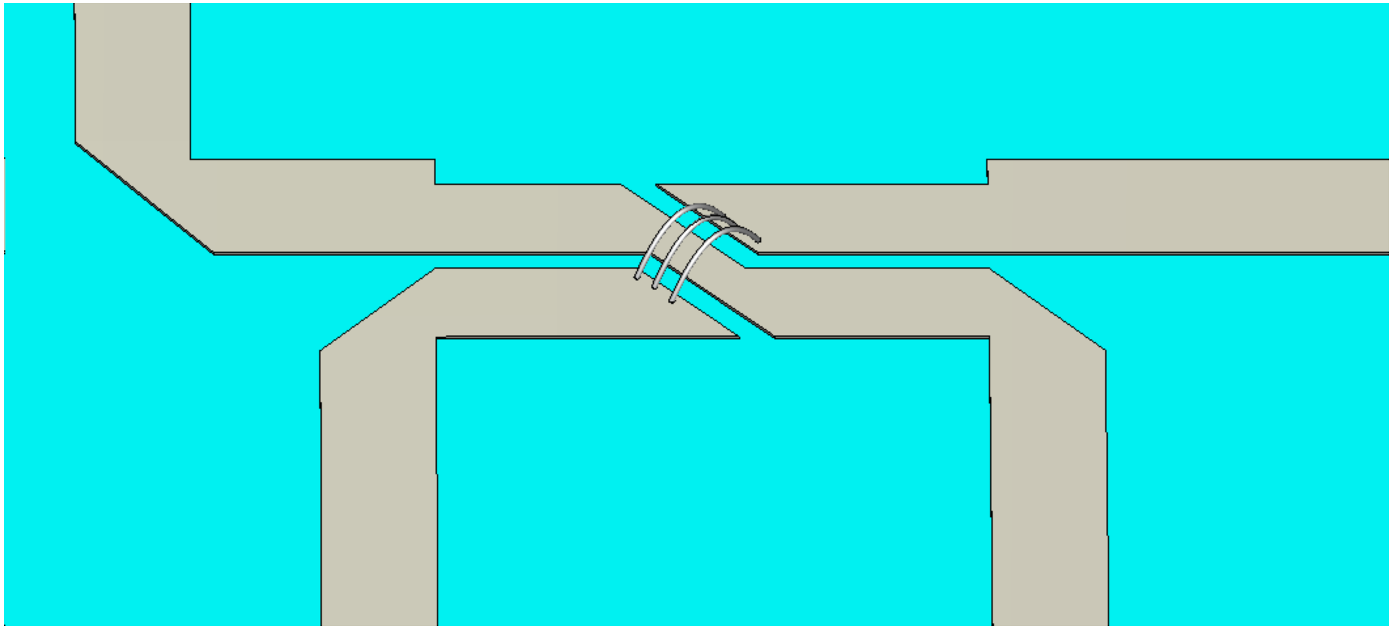
90-Degree Hybrid Coupler Design

- Layout of twisted tandem couplers



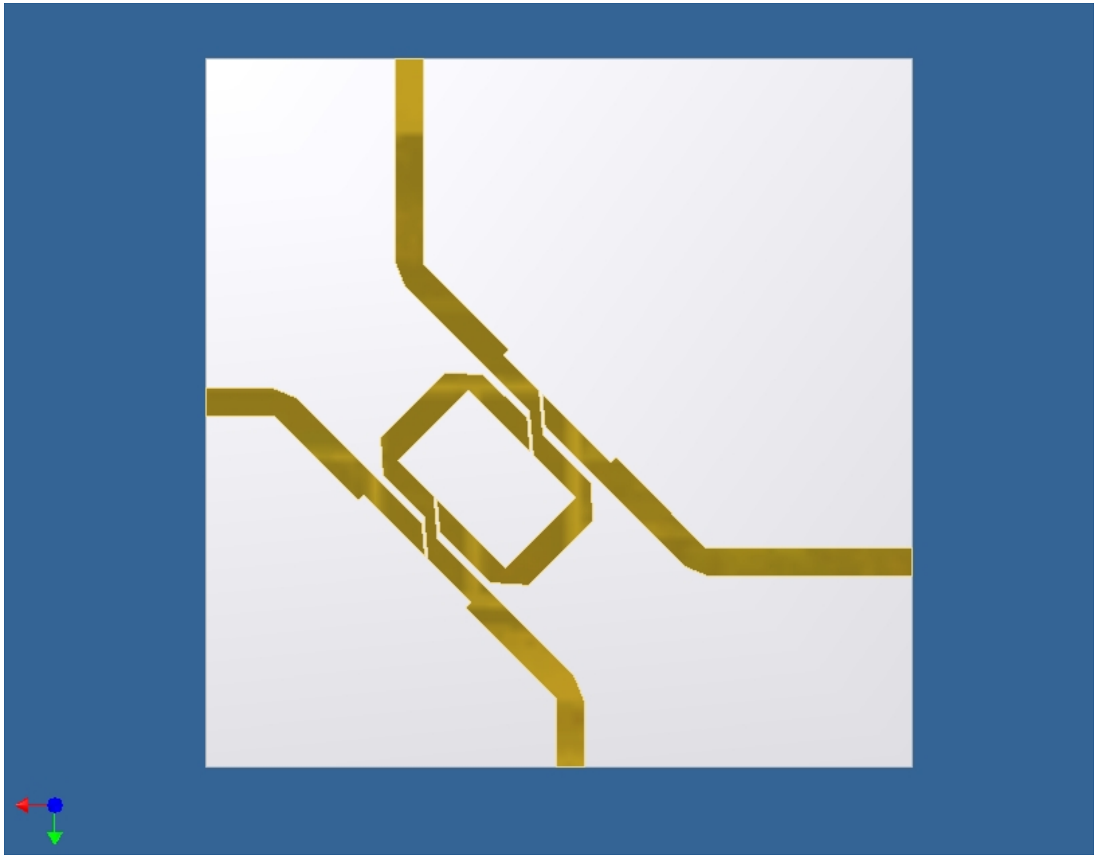
90-Degree Hybrid: CST Model

- Wire bond locations



90-Degree Hybrid Chip

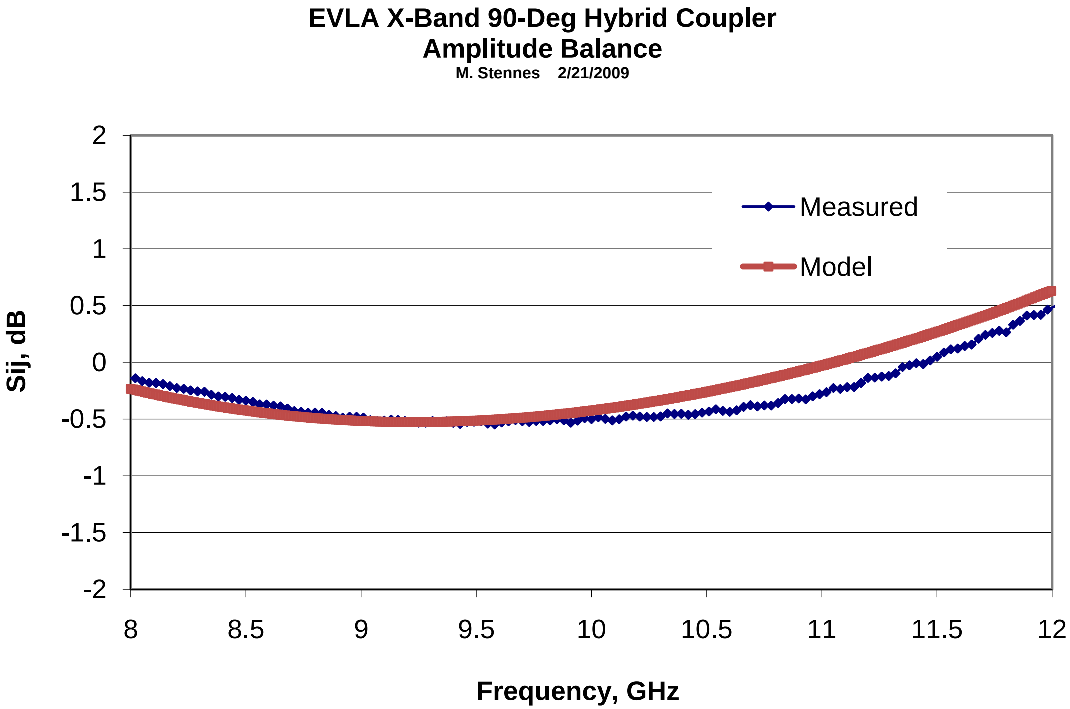
- Inventor Model



EVLA

90-Degree Hybrid: Measured Performance

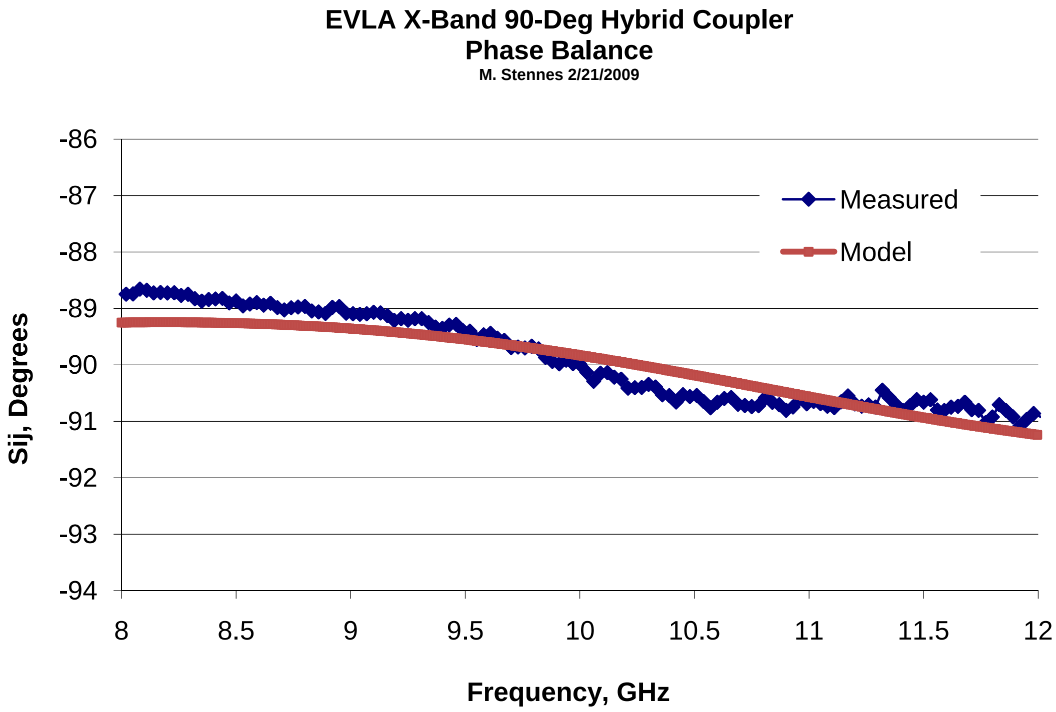
- Amplitude Balance



NRAO

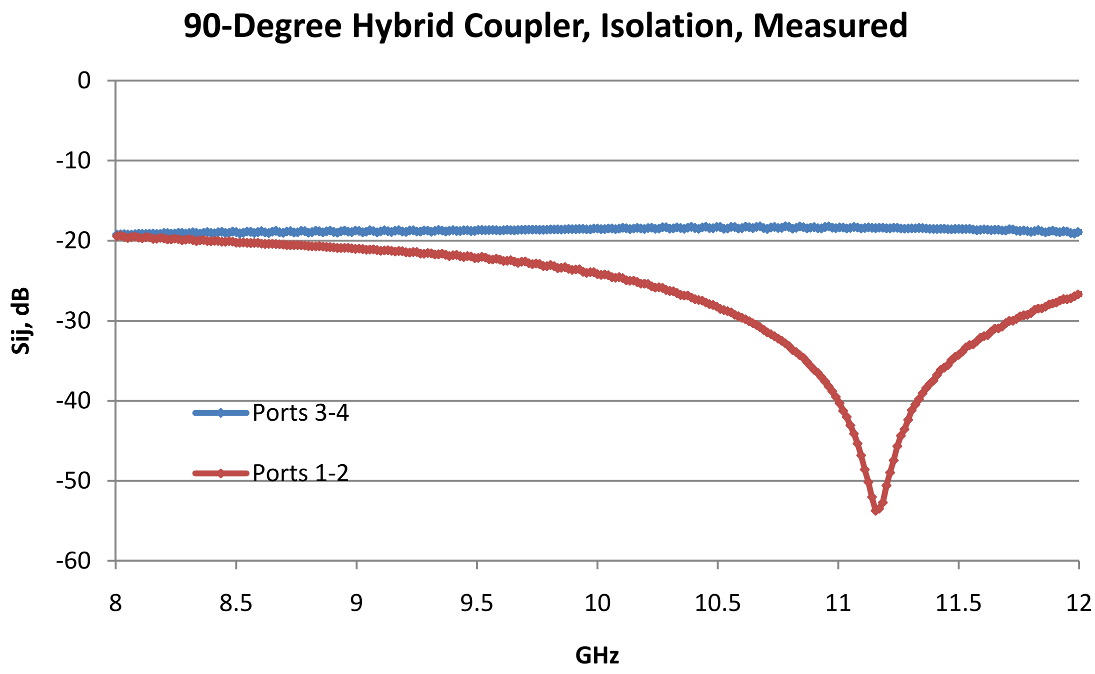
90-Degree Hybrid: Measured Performance

- Phase Balance



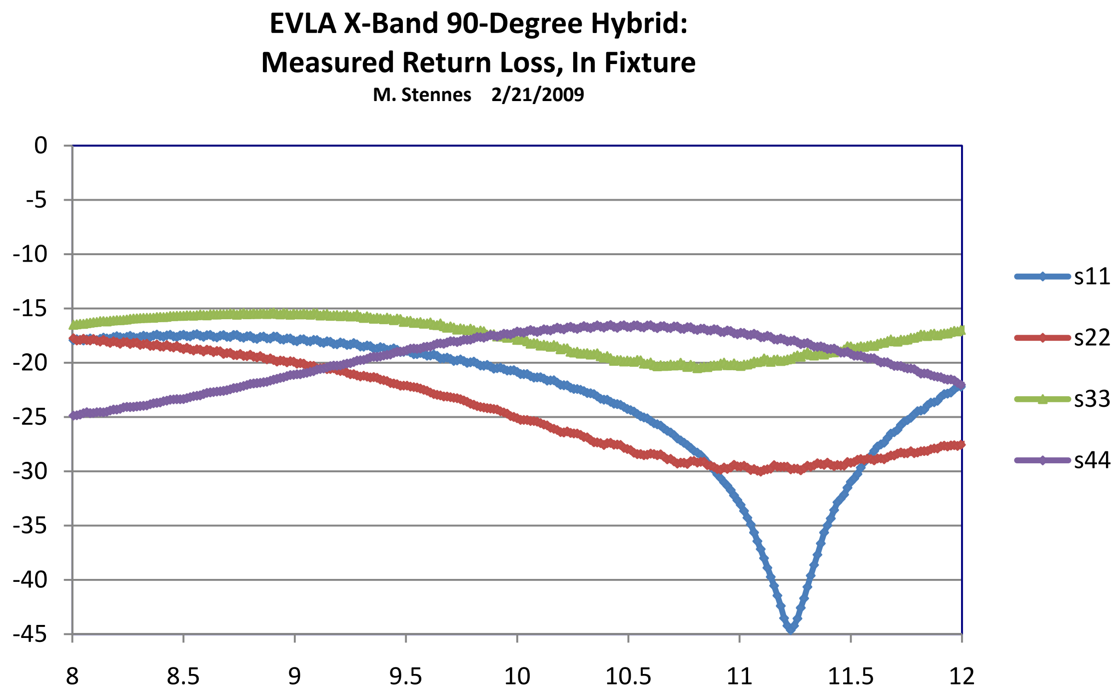
90-Degree Hybrid: Measured Performance

- Isolation



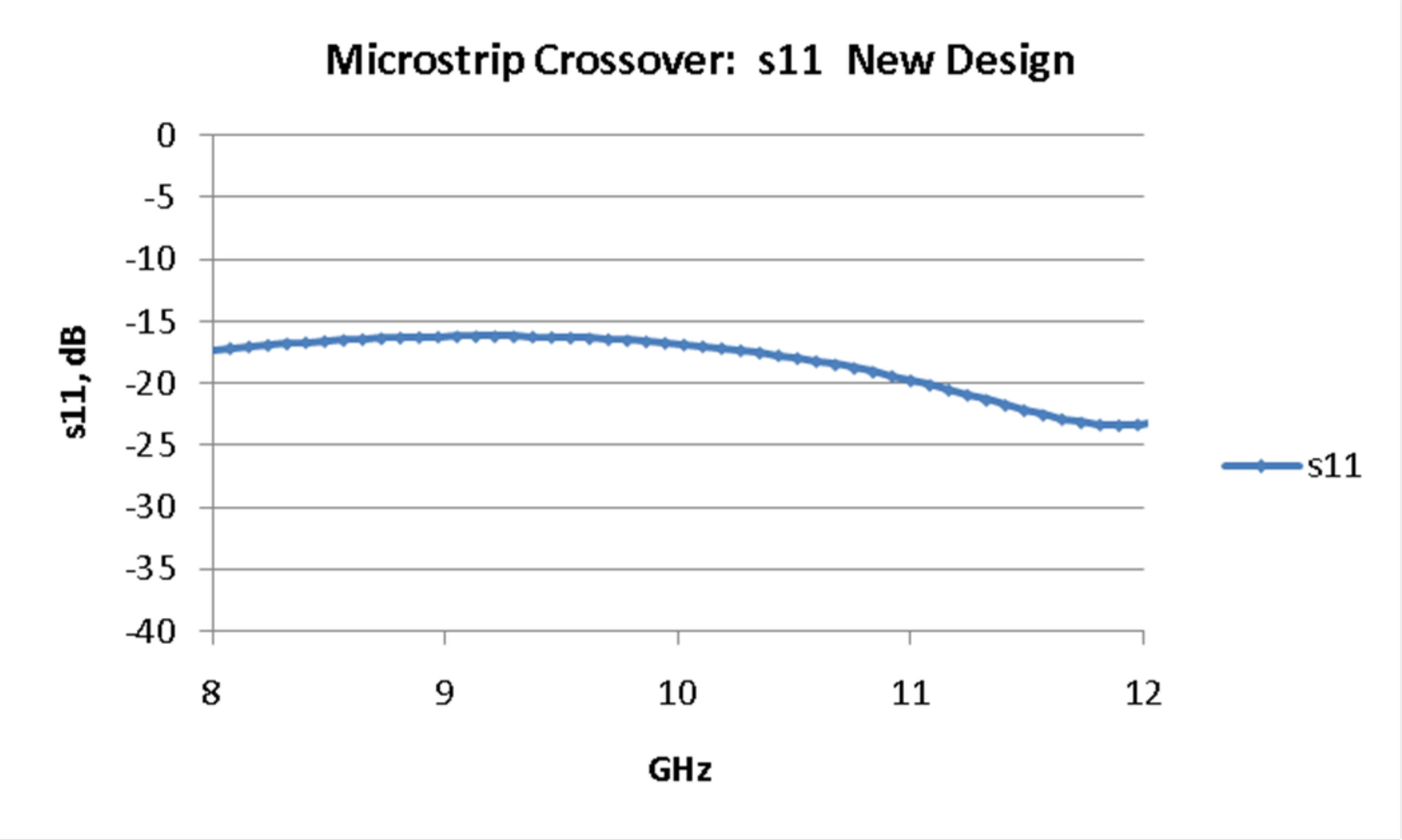
90-Degree Hybrid: Measured Performance

- Reflection Coefficient



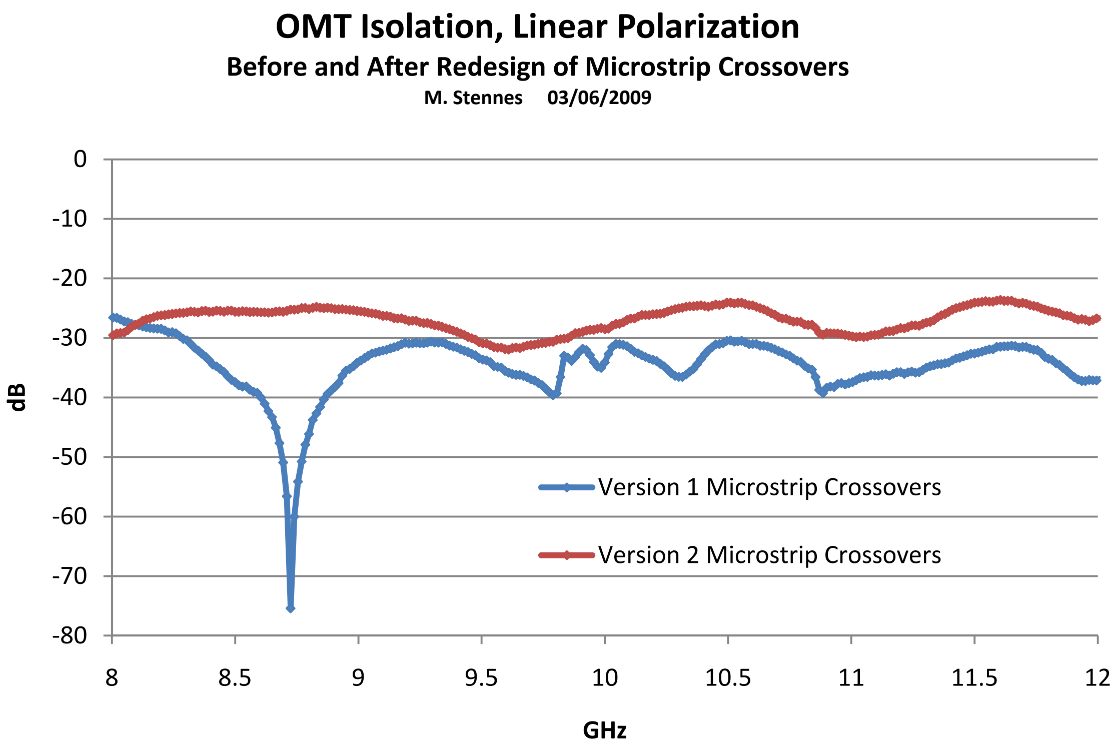
Microstrip Crossover, New Design

- s11



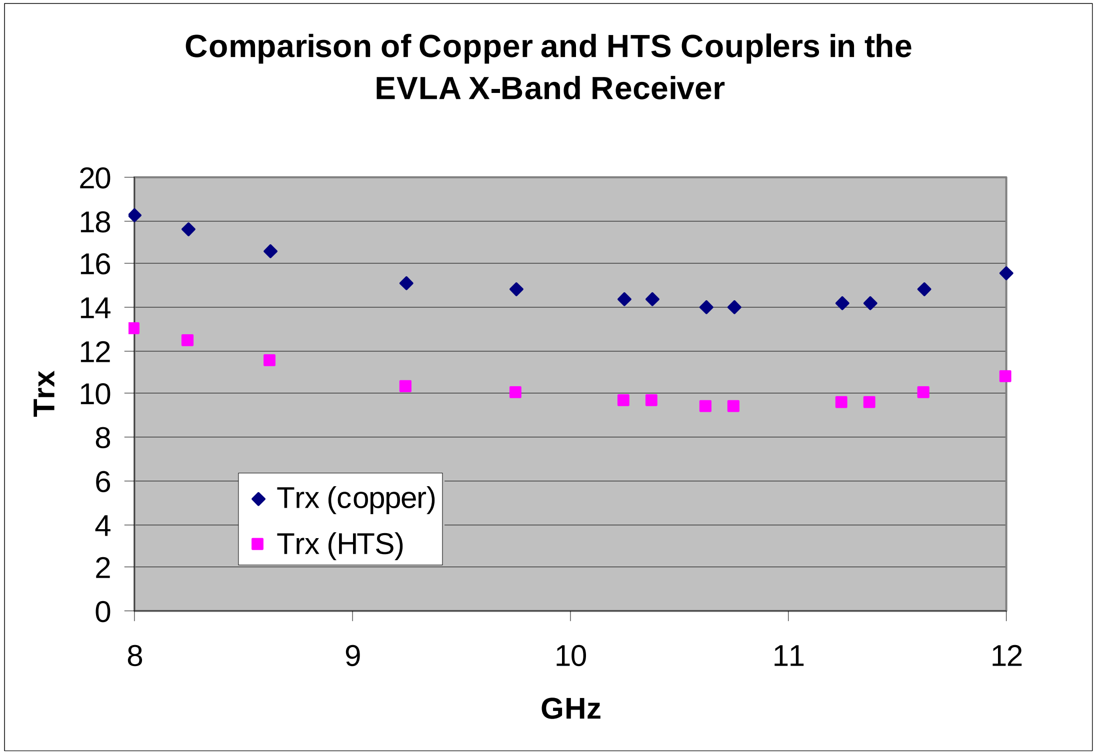
Microstrip Crossover

- Measured Results



Receiver Noise Temperature Prediction

- Comparison between Copper and YBCO



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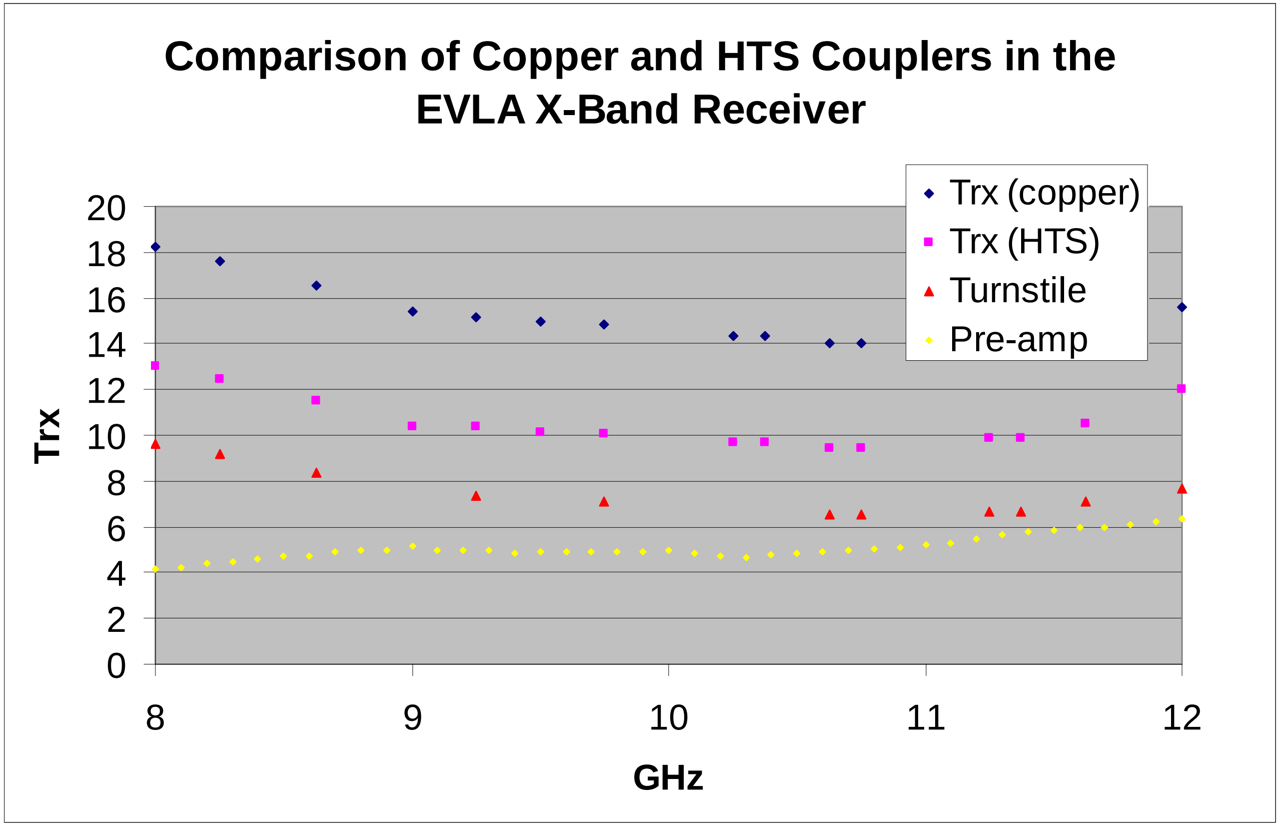
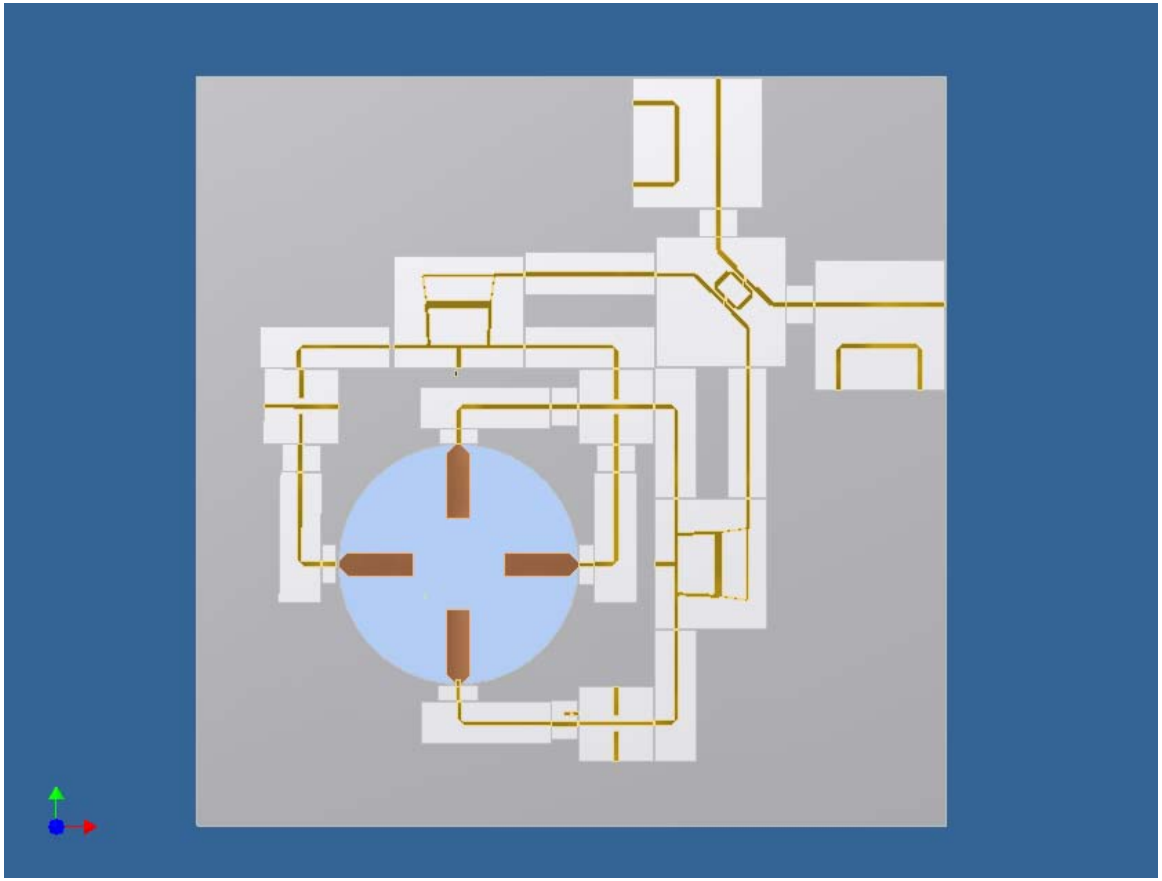
Receiver Noise Temperature Predictions

- MMIC LNA Option



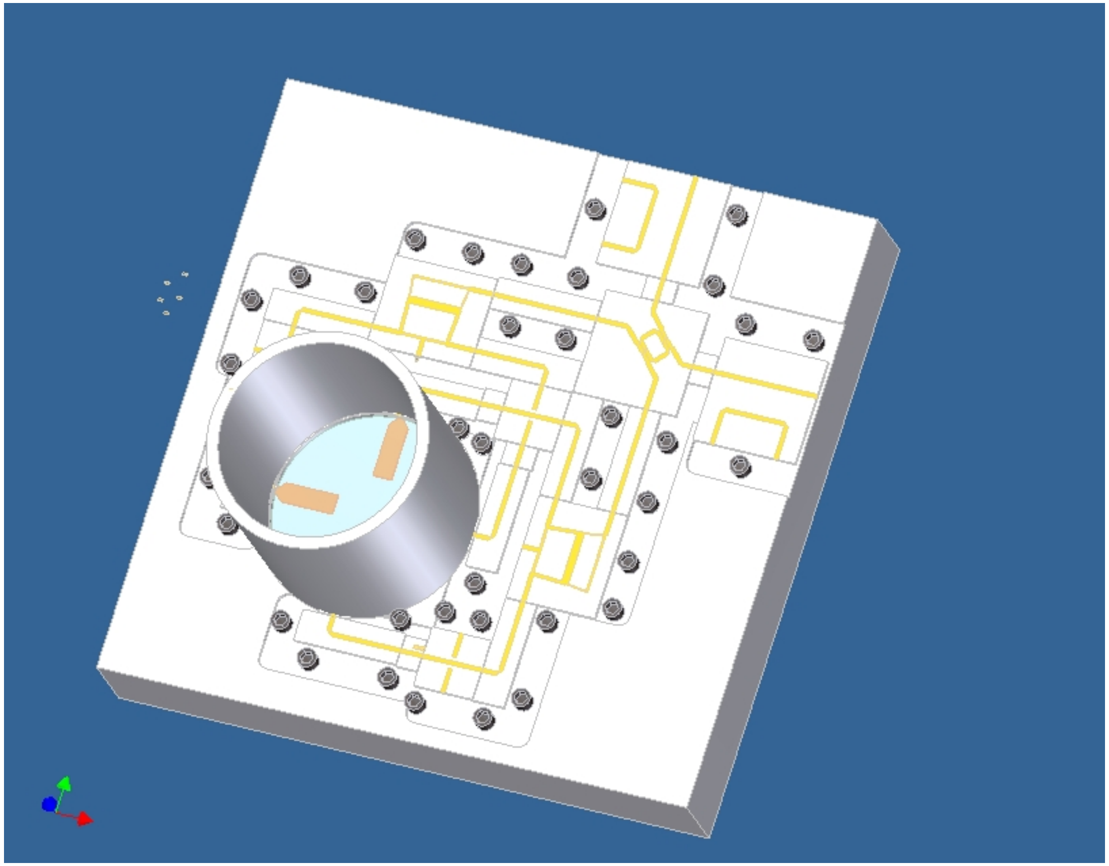
OMT Circuit Layout

- Inventor Model



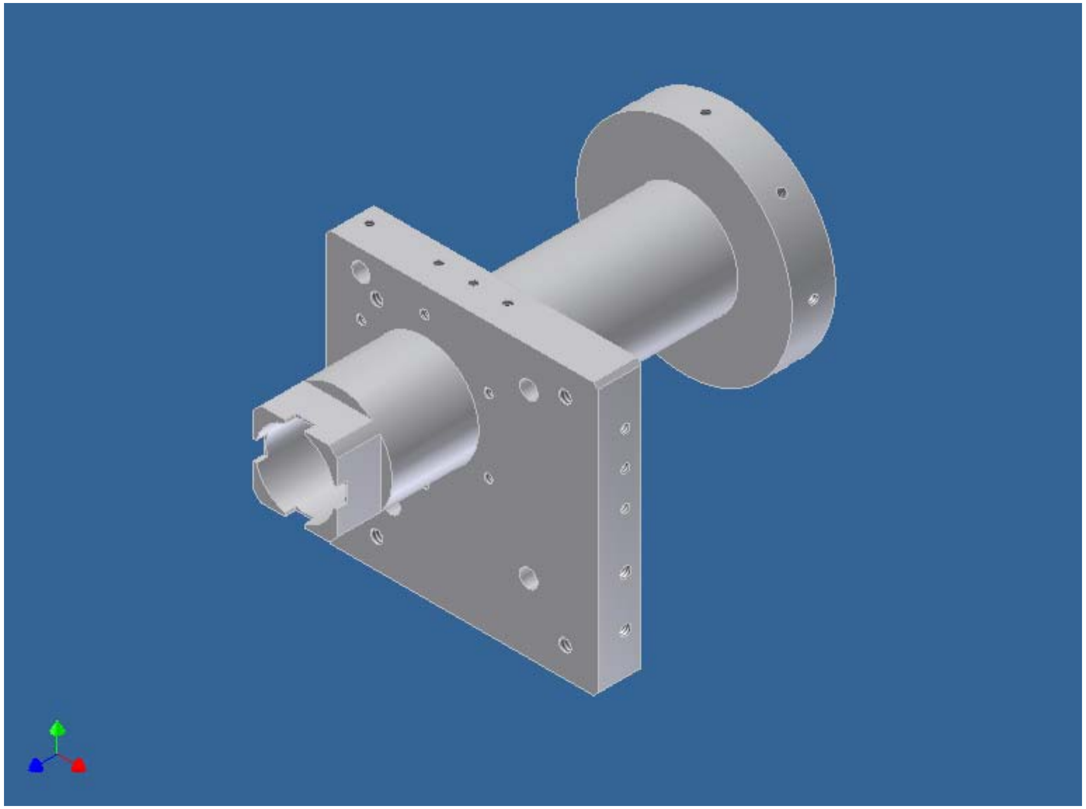
Chip Mounting

- Inventor Model



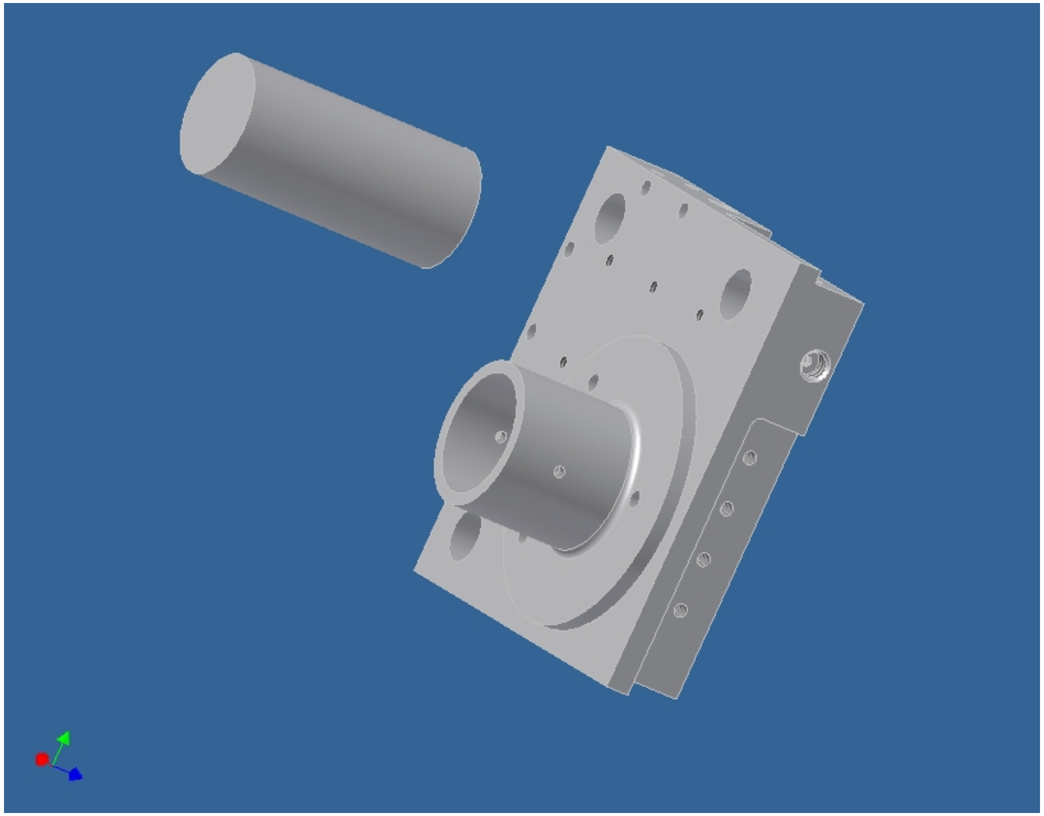
50 K Waveguide Section

- Inventor Model



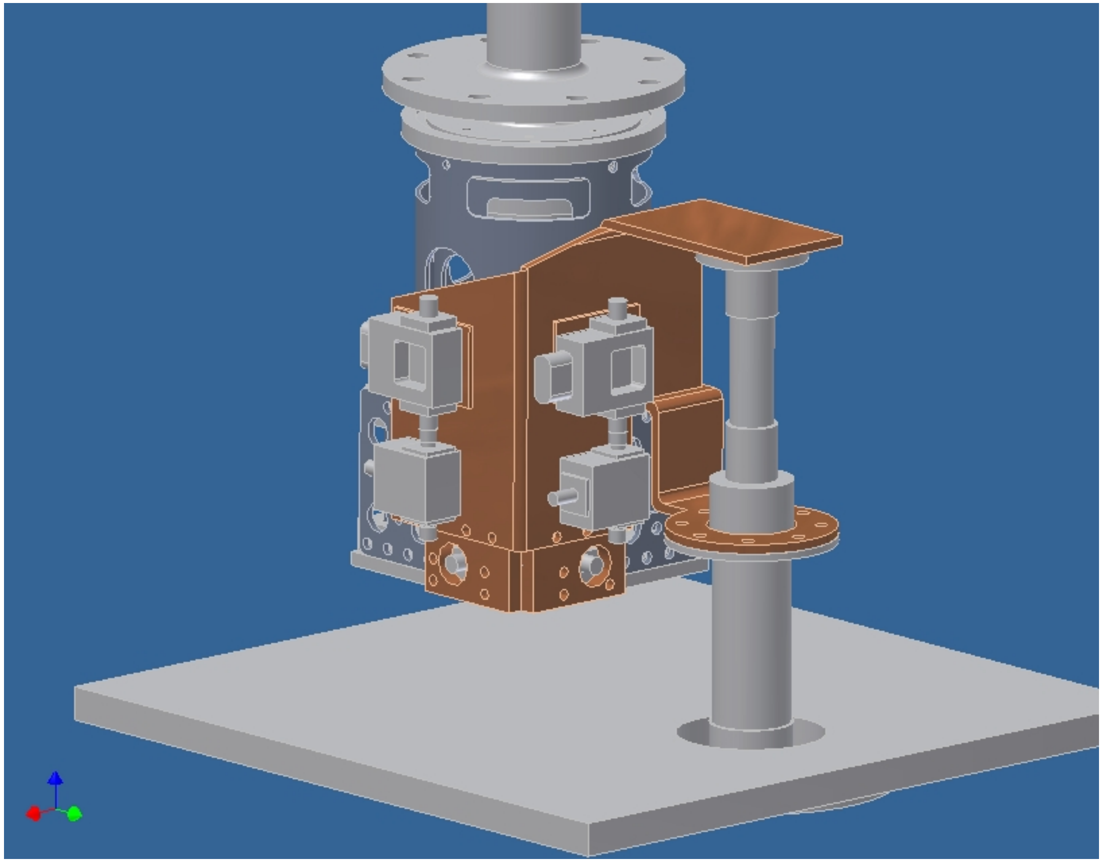
OMT with Sliding Backshort

- Inventor Model



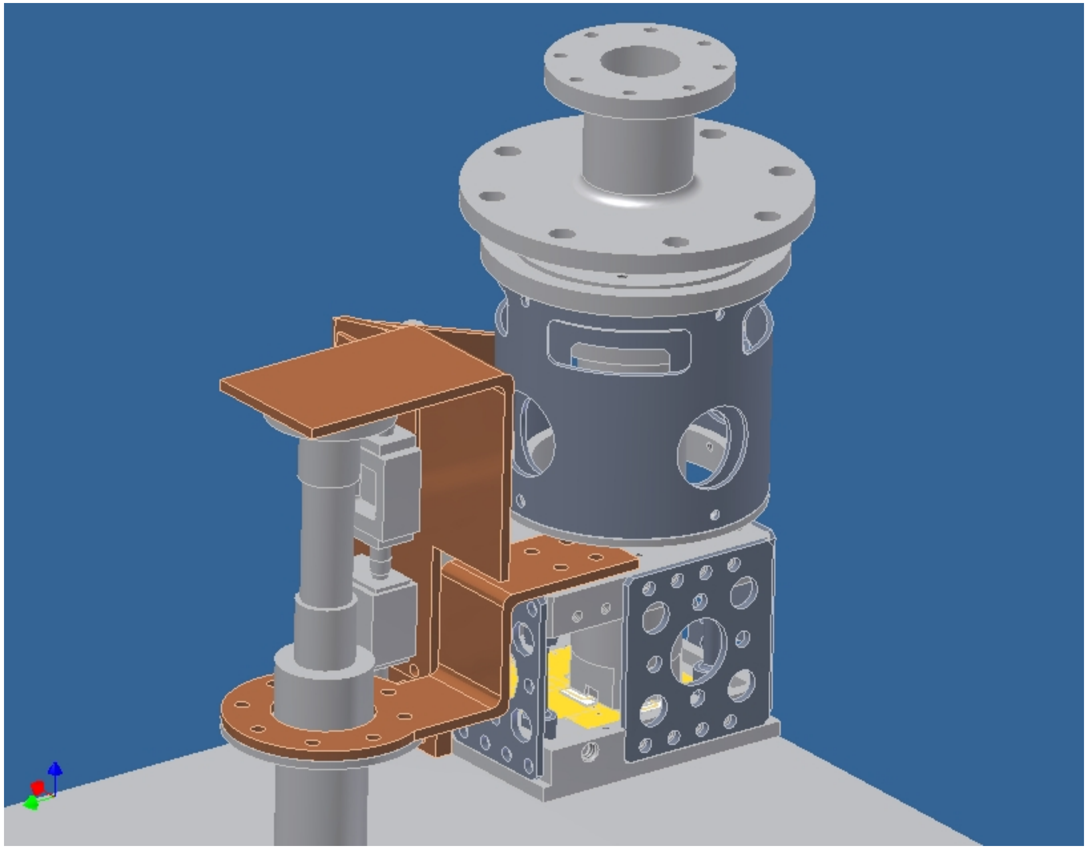
Cryostat

- Inventor Model: Second Stage Cold Plate



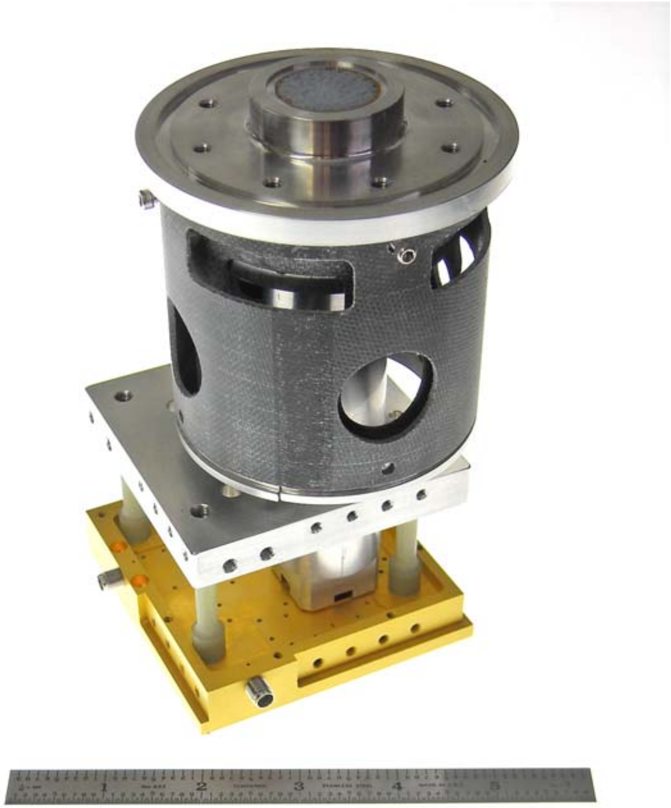
Cryostat

- Inventor Model: First Stage Cold Plate



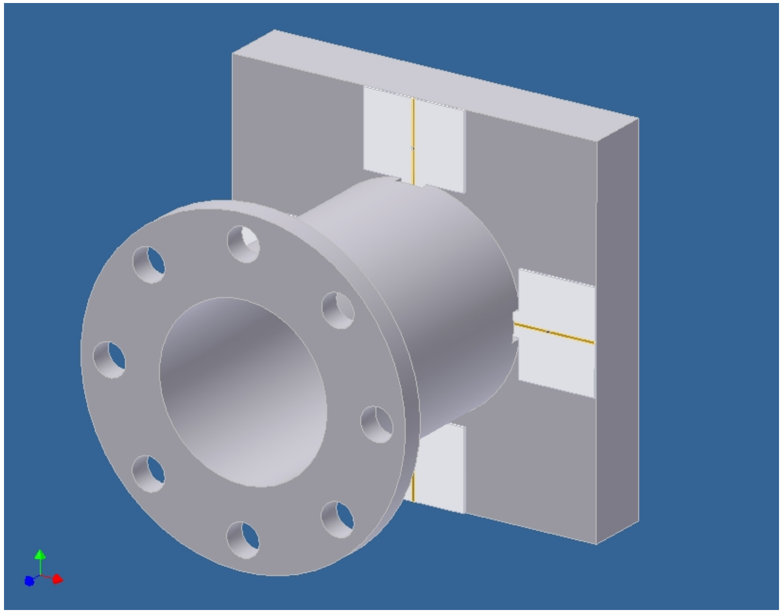
Vacuum Window, Thermal Transitions

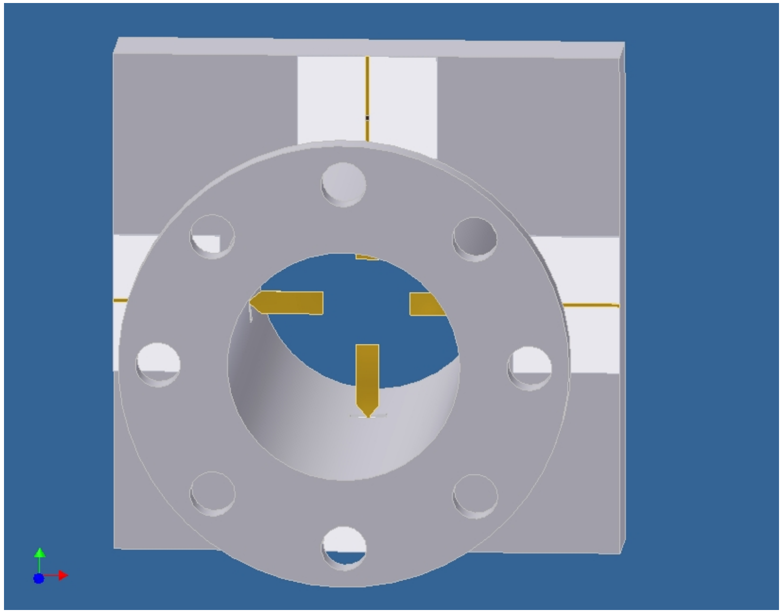
- Input WG



WG Probe Interface to Microstrip

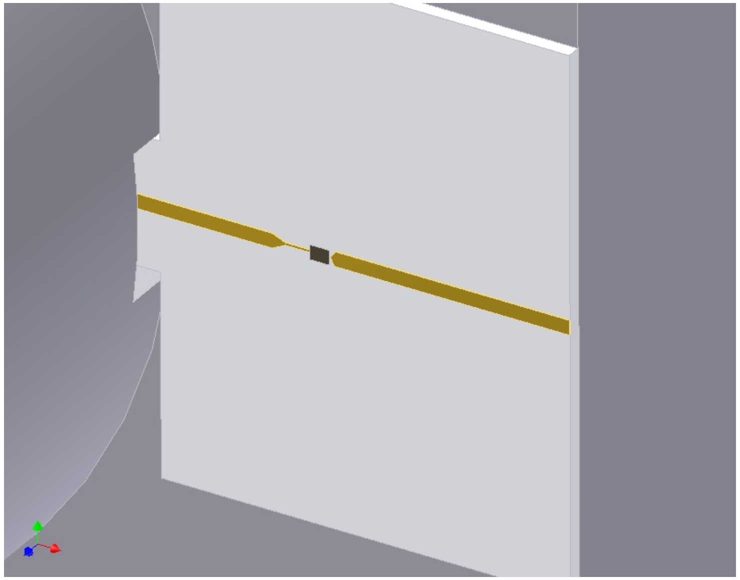
- Microstrip

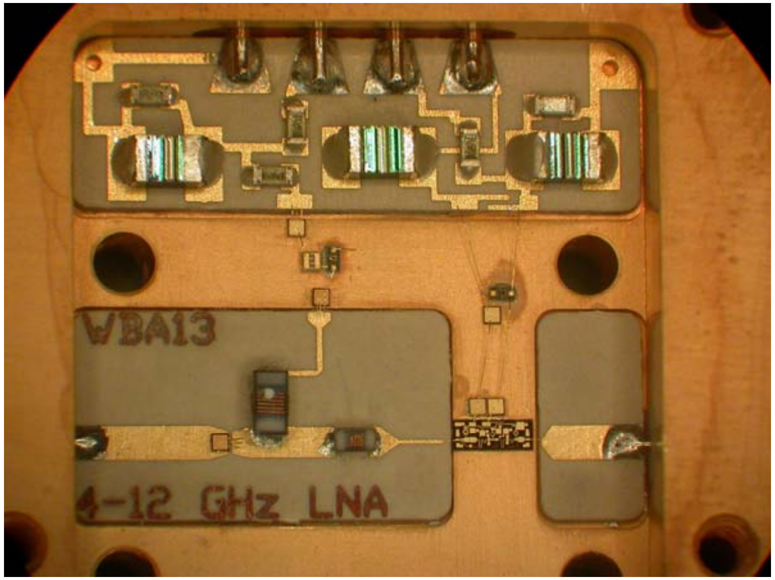




MMIC Option

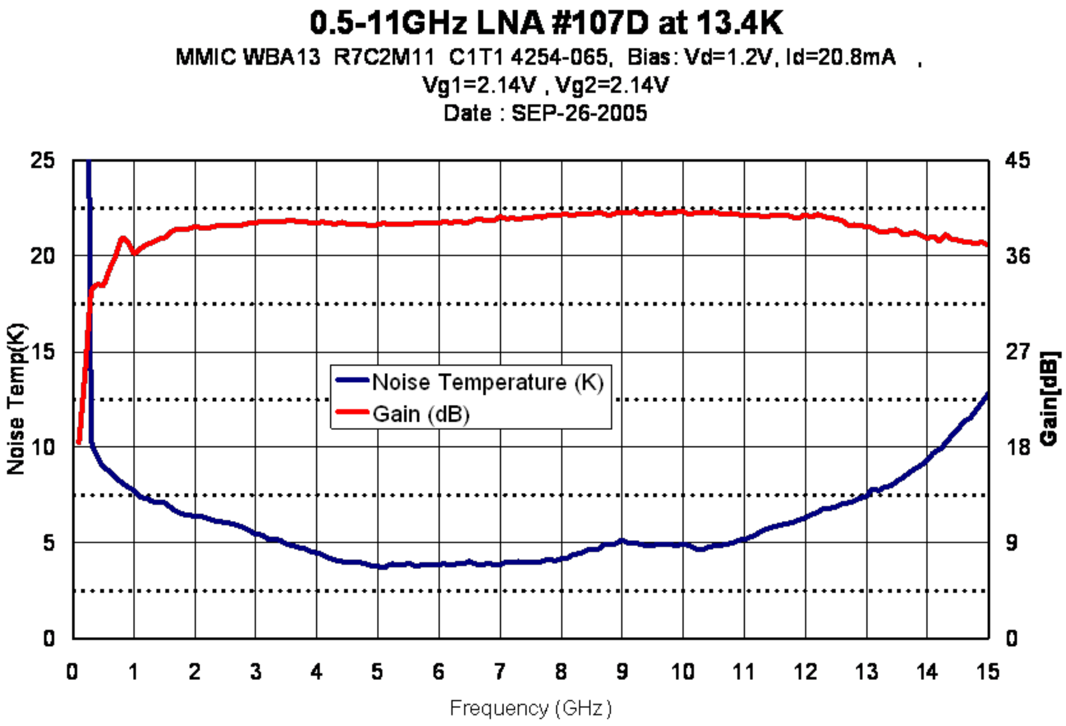
- MMIC LNA





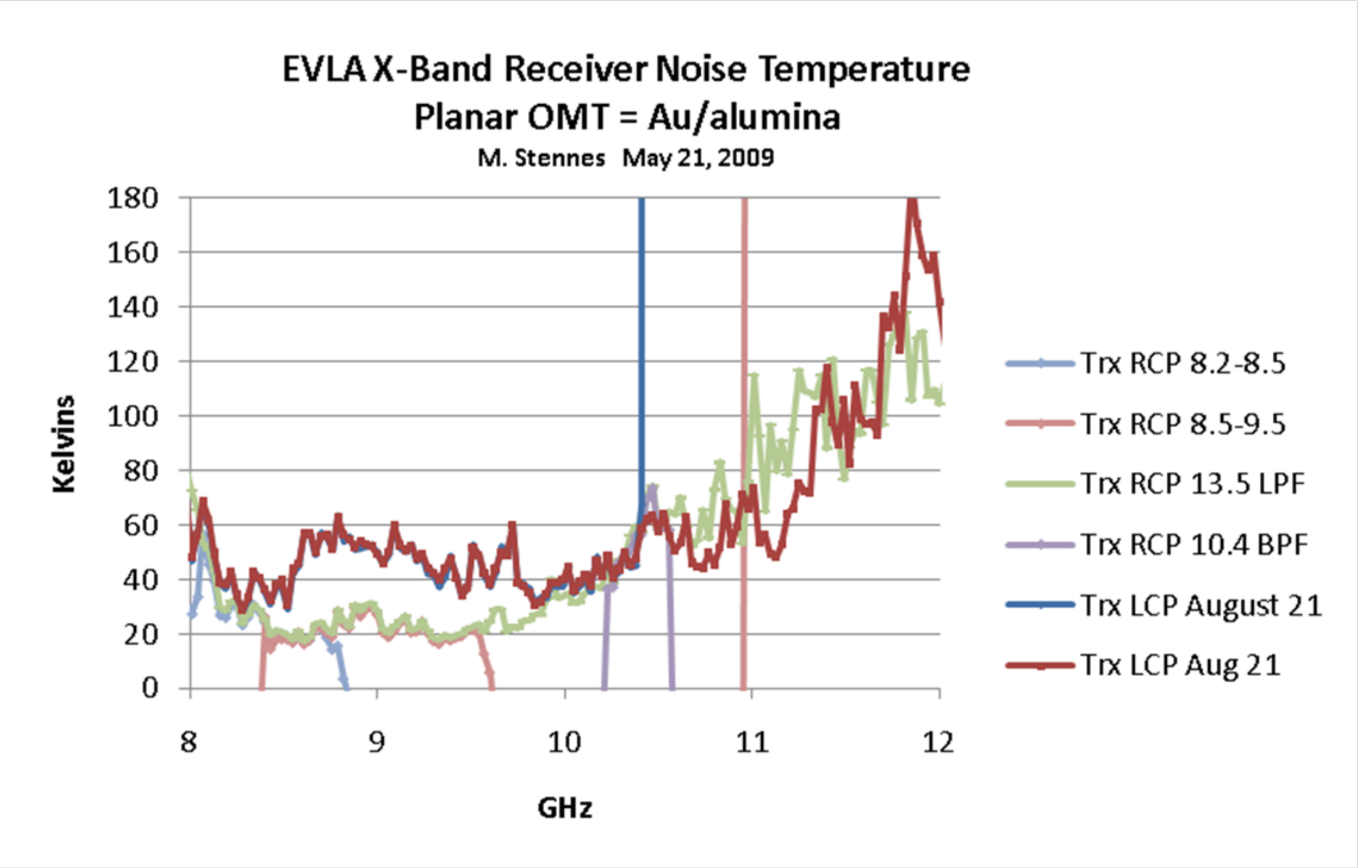
MMIC Performance

- Measured Data from Sandy Weinreb



Receiver Noise Temperature

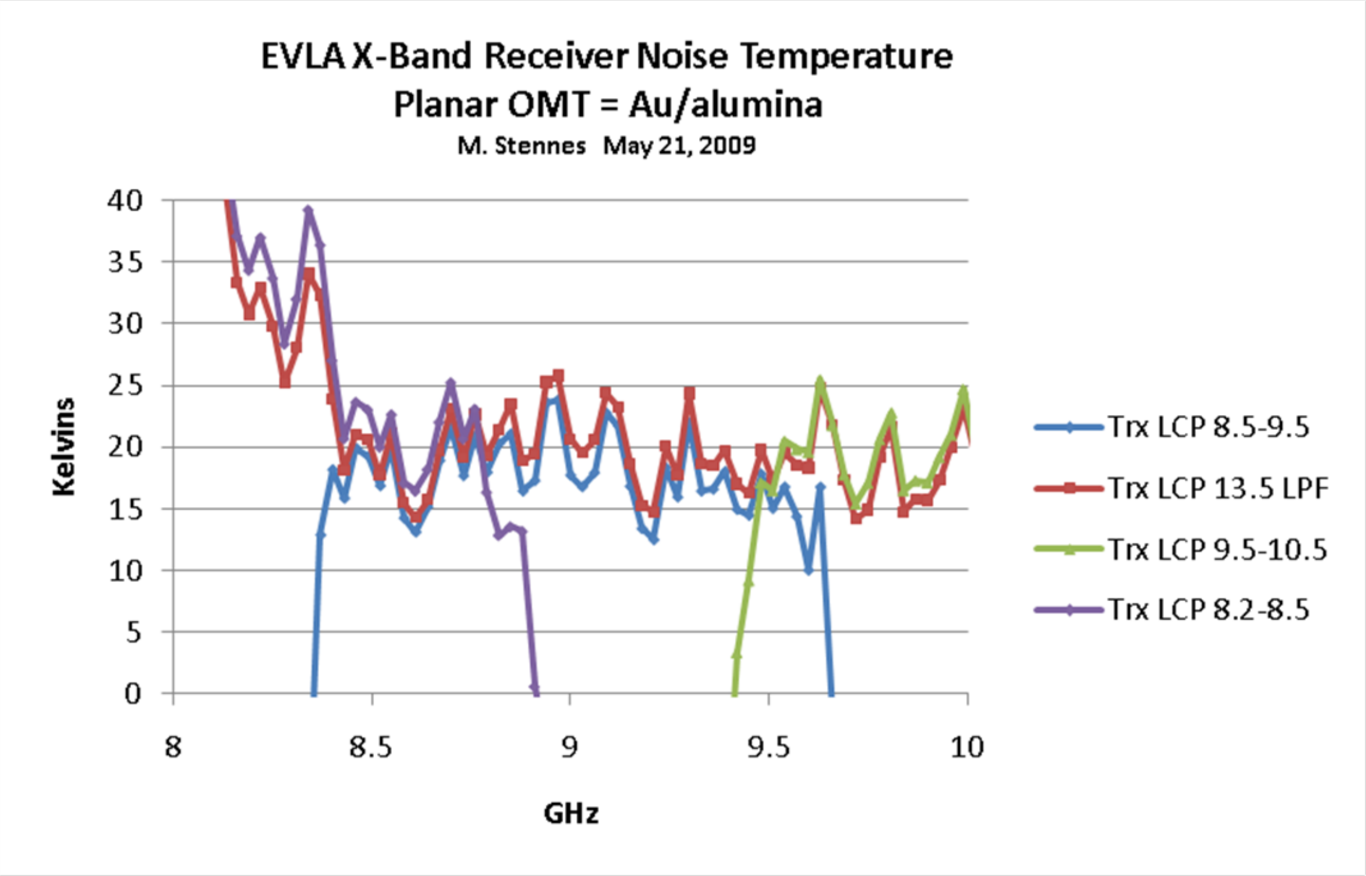
- Gold/Alumina OMT



EVLA

Receiver Noise Temperature

- Gold/Alumina OMT



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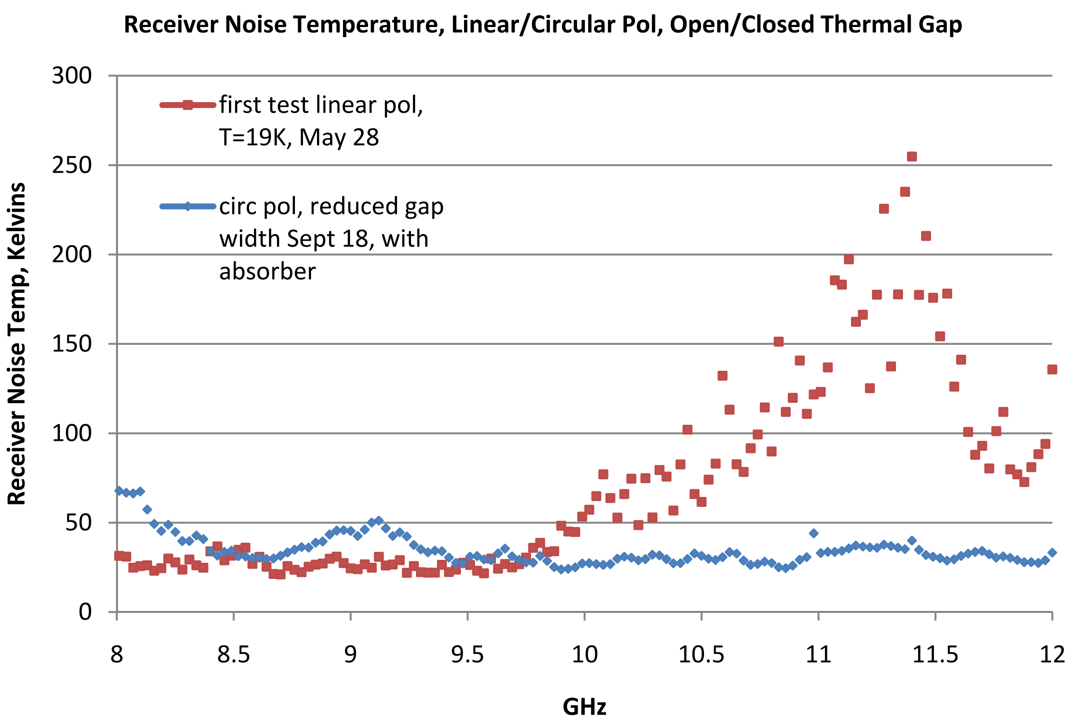
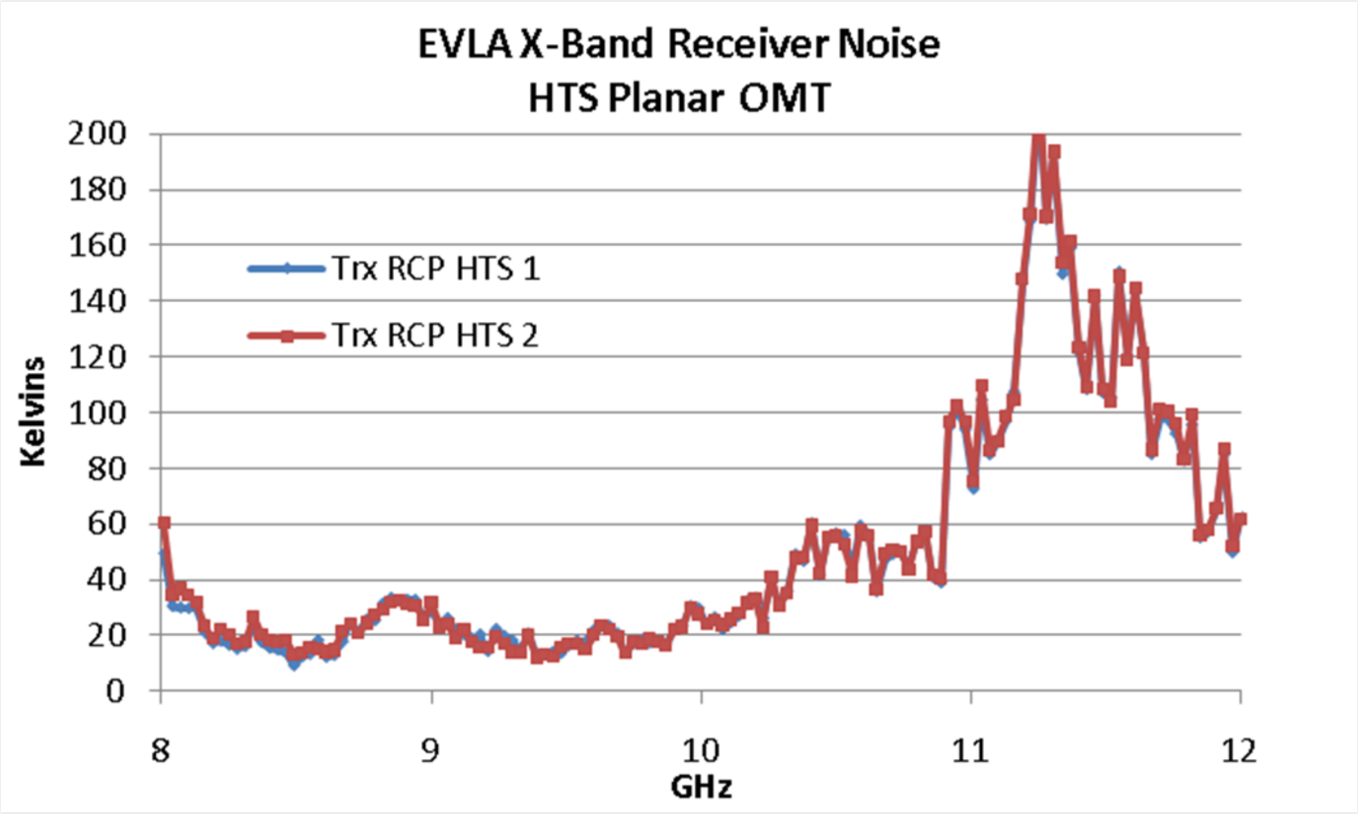
Receiver Noise Temperature

- Linear vs. Circular Polarization
- Thermal Gap Open, Closed



Receiver Noise Temperature

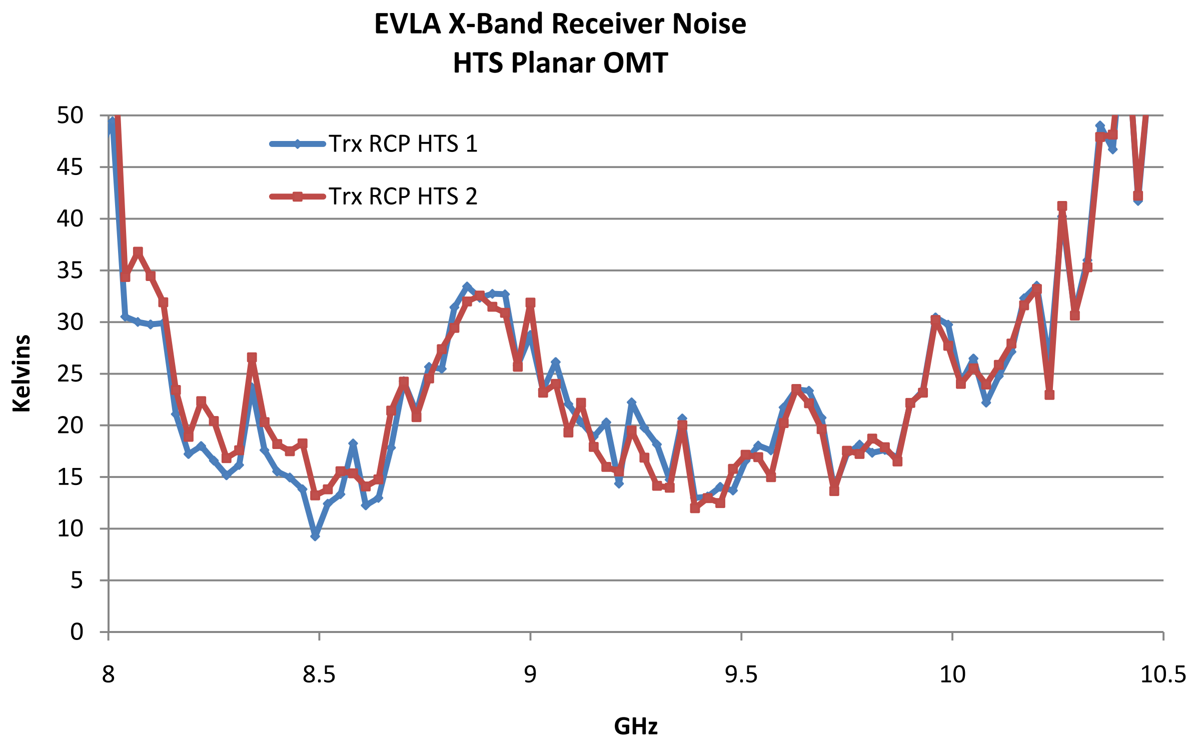
- YBCO/MgO OMT



Receiver Noise Temperature

EVLA

- YBCO/MgO OMT



NRAO

Receiver Noise, HTS OMT

- 3 GHz IF

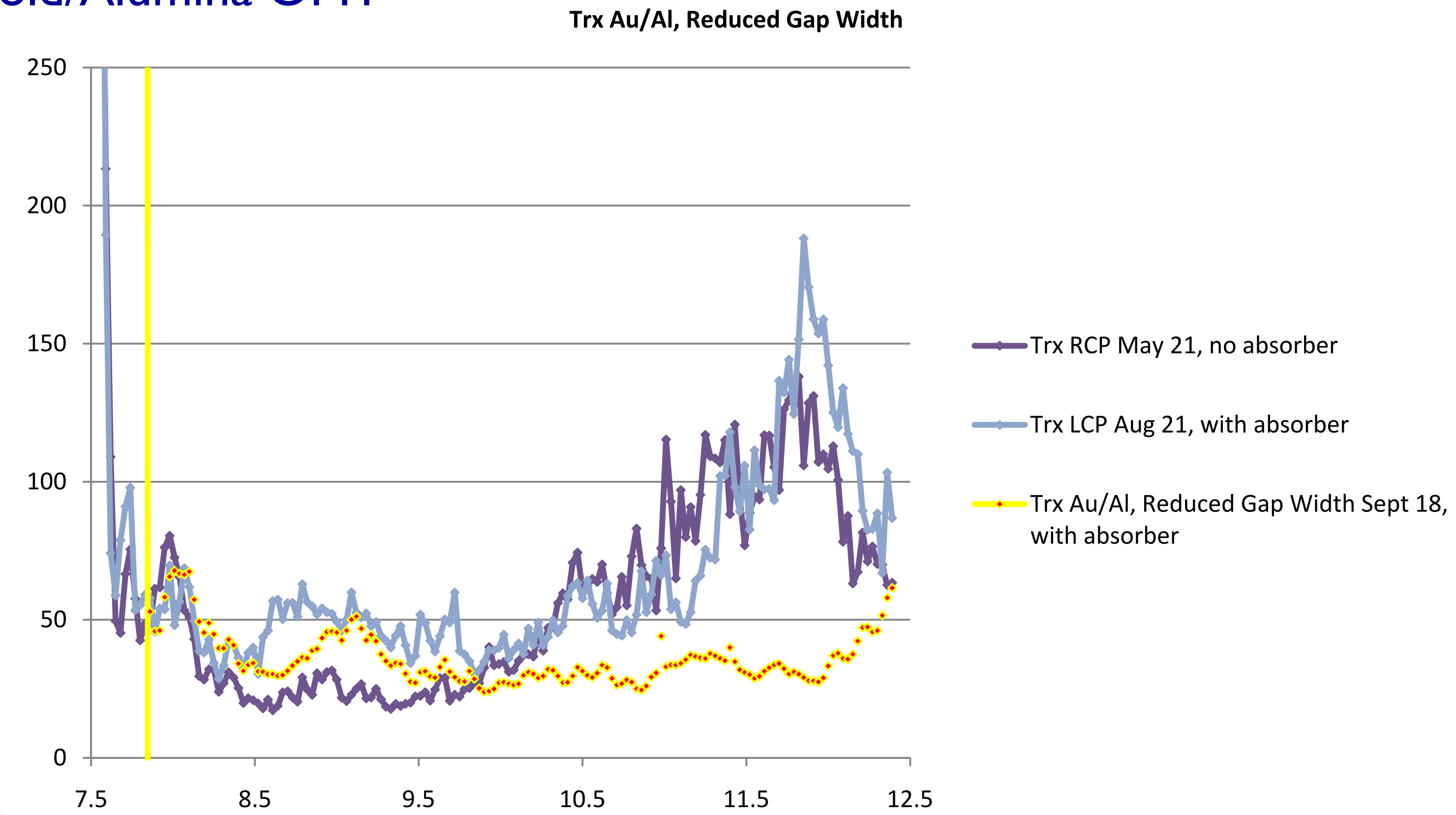
This data was taken using a power meter, measuring 3GHz IF, filtered through a tunable microwave preselector.
Receiver configuration is HTS OMT, old TRW cryo isolators.

	Thot	Tcold				
	298	81				
f (GHz)	Phot (dBm)	Pcold(dBm)	Y(dB)	Y	Trx (K)	
8	-24.93	-29.17	4.24	2.654606	50.14908	
8.1	-25.05	-29.79	4.74	2.978516	28.67814	
8.2	-23.89	-28.96	5.07	3.213661	17.02768	
8.3	-24.11	-29.22	5.11	3.243396	15.72835	
8.4	-22.91	-28.19	5.28	3.372873	10.45032	
8.5	-22.9	-28.22	5.36	3.435579	8.09584	
8.6	-23.21	-28.52	5.31	3.396253	9.558061	RCP
8.7	-23.52	-28.62	5.1	3.235937	16.05105	
8.8	-24.22	-29.11	4.89	3.083188	23.16727	
8.9	-24.63	-29.55	4.92	3.10456	22.10946	
9	-25.14	-30.1	4.96	3.133286	20.72102	
9.5	-24.98	-30.03	5.05	3.198895	17.68593	
10	-26.05	-30.84	4.79	3.013006	26.79898	
10.5	-27.67	-32.04	4.37	2.735269	44.05268	
11	-29.04	-32.56	3.52	2.249055	92.7314	
11.5	-32.63	-35.8	3.17	2.074914	120.8767	
12	-31.32	-35	3.68	2.333458	81.73478	
12.5						

NRAO

Receiver Noise Temperature

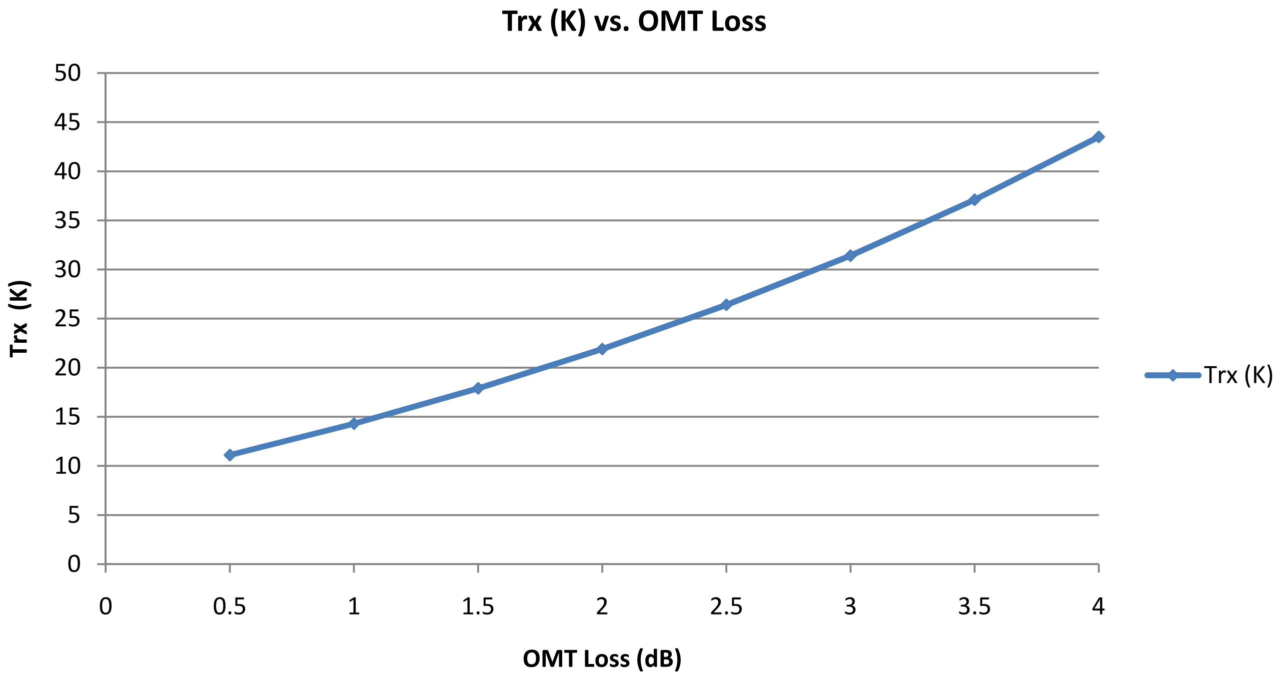
- Gold/Alumina OMT



Note: Noise in 8.5-9.5 GHz is higher, maybe due to degradation to circuits

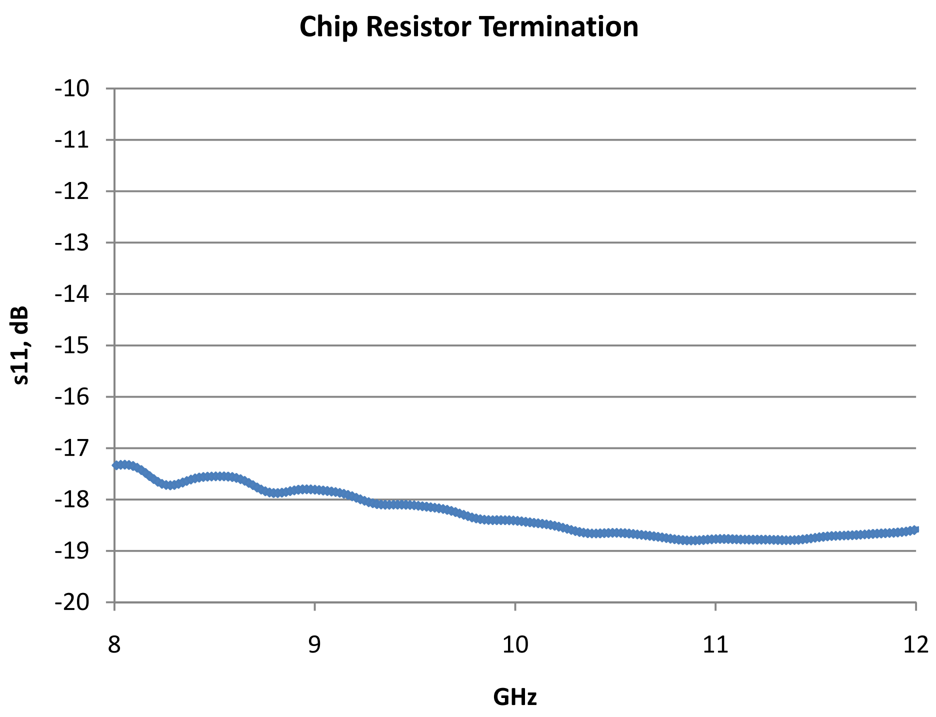
Trx as a Function of OMT Loss

- Trx vs OMT Loss



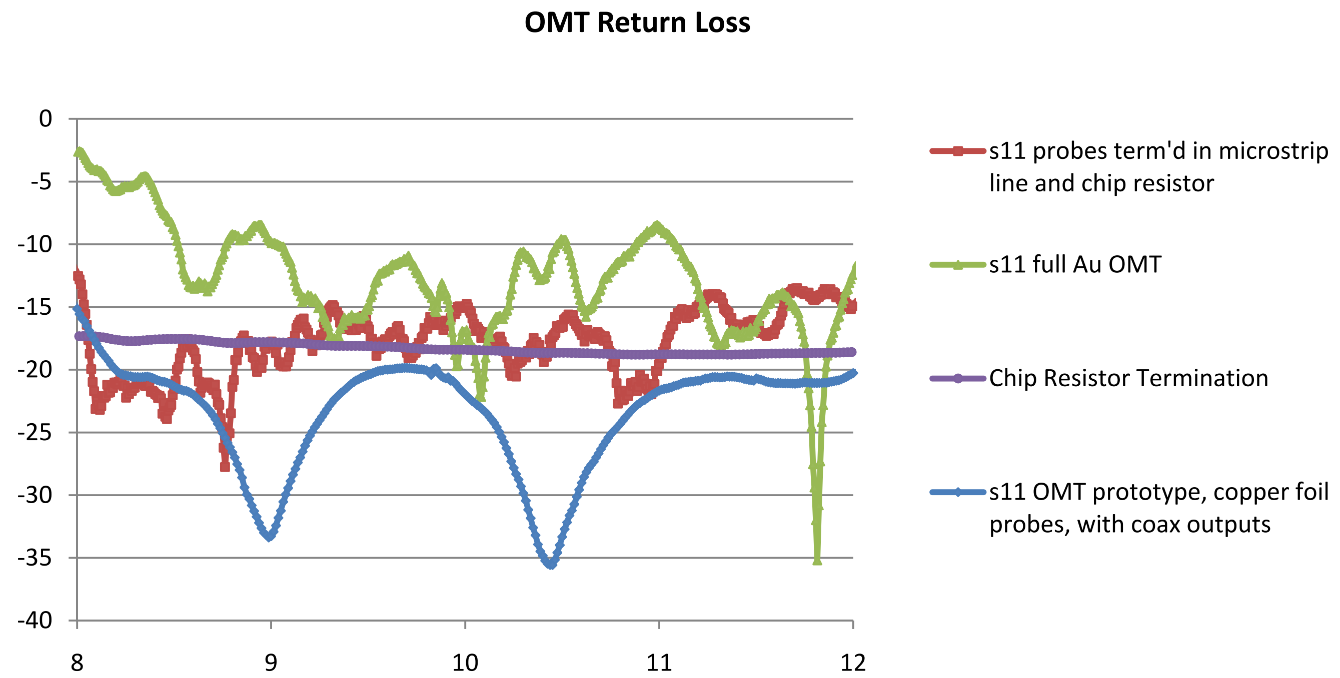
Chip Resistor Return Loss

- Chip Resistor 0210, s11



OMT Input Return Loss

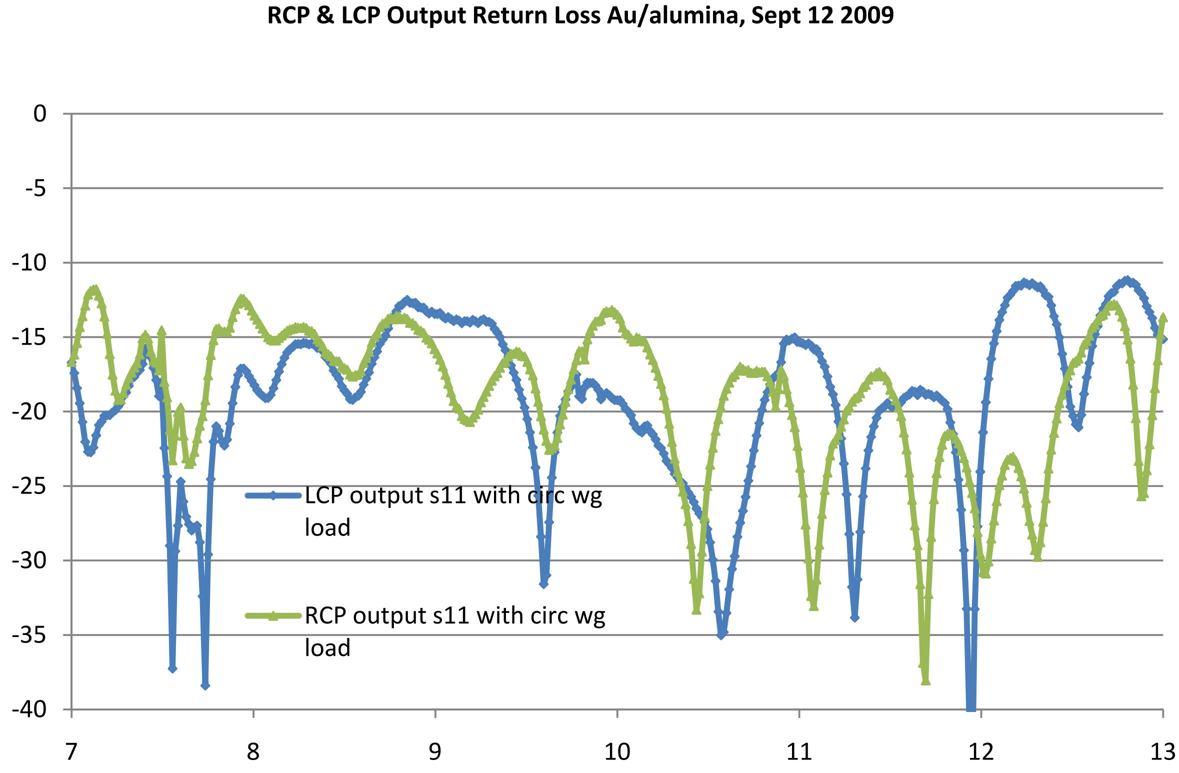
- Full OMT vs. Chip Resistor Terminated Probes



EVLA

OMT Output Return Loss

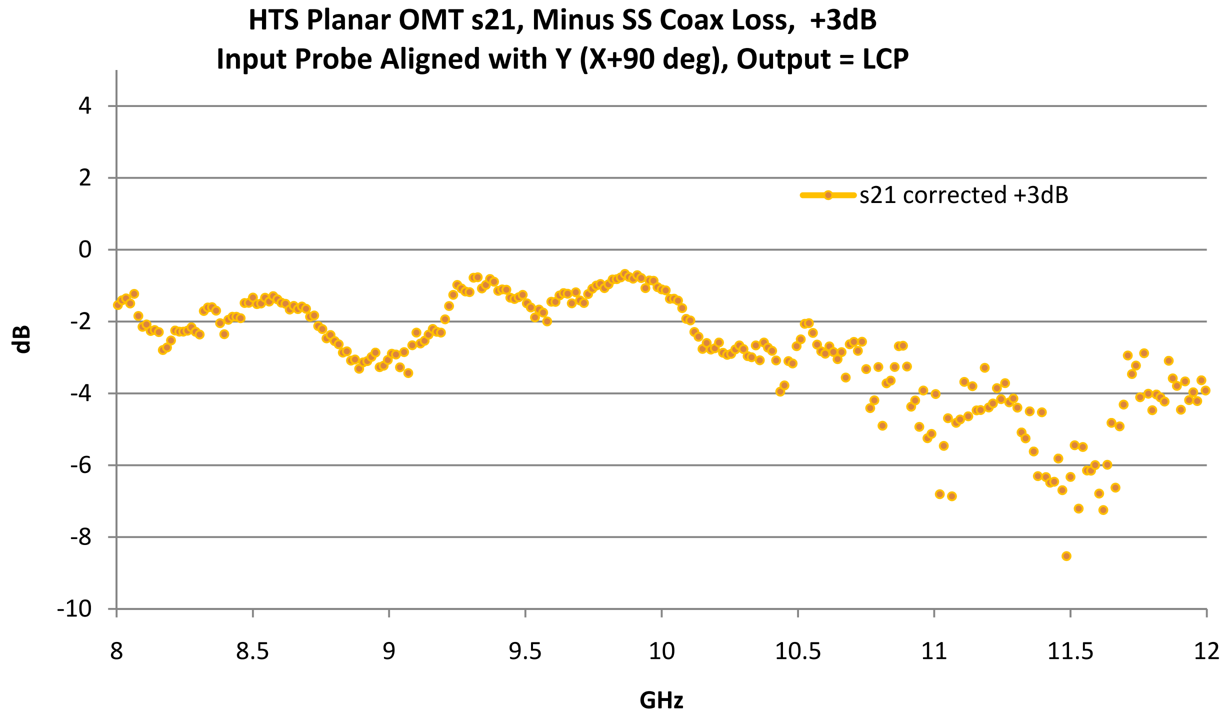
- S22, S33



NRAO

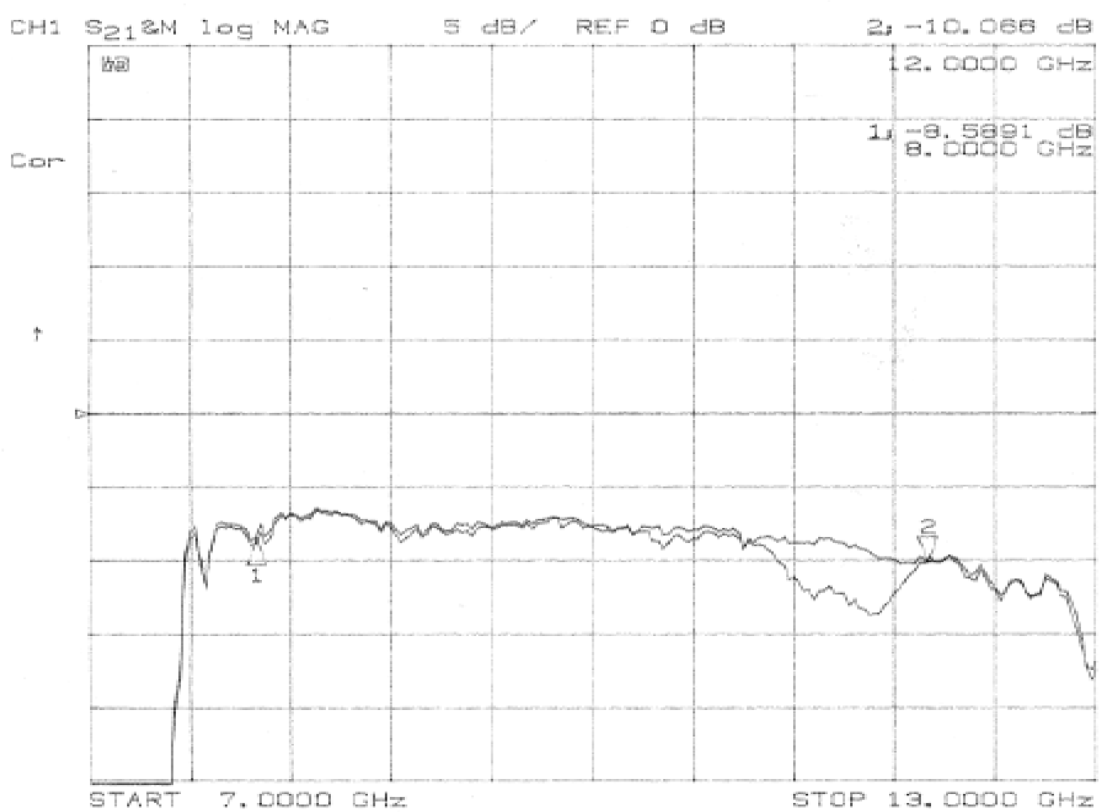
YBCO OMT Loss

- SS Coax Loss, and 3 dB Coupling Loss Removed from Measured Data



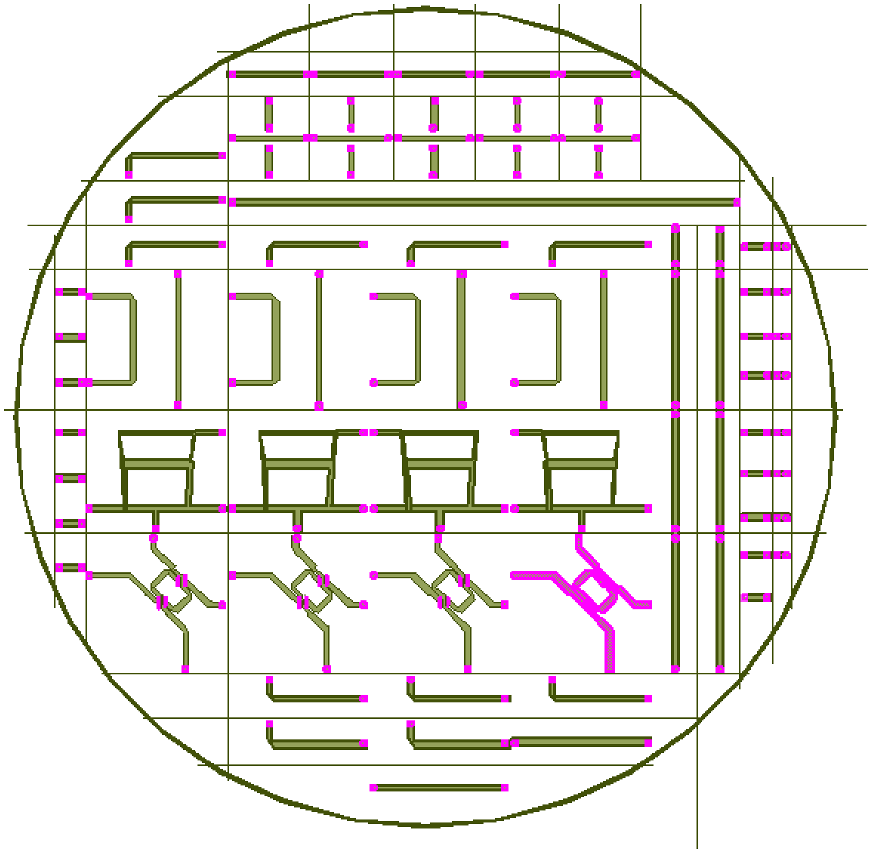
Closing the 15K/50K WG Thermal Gap

- Au/Alumina OMT, Room Temperature Measurements



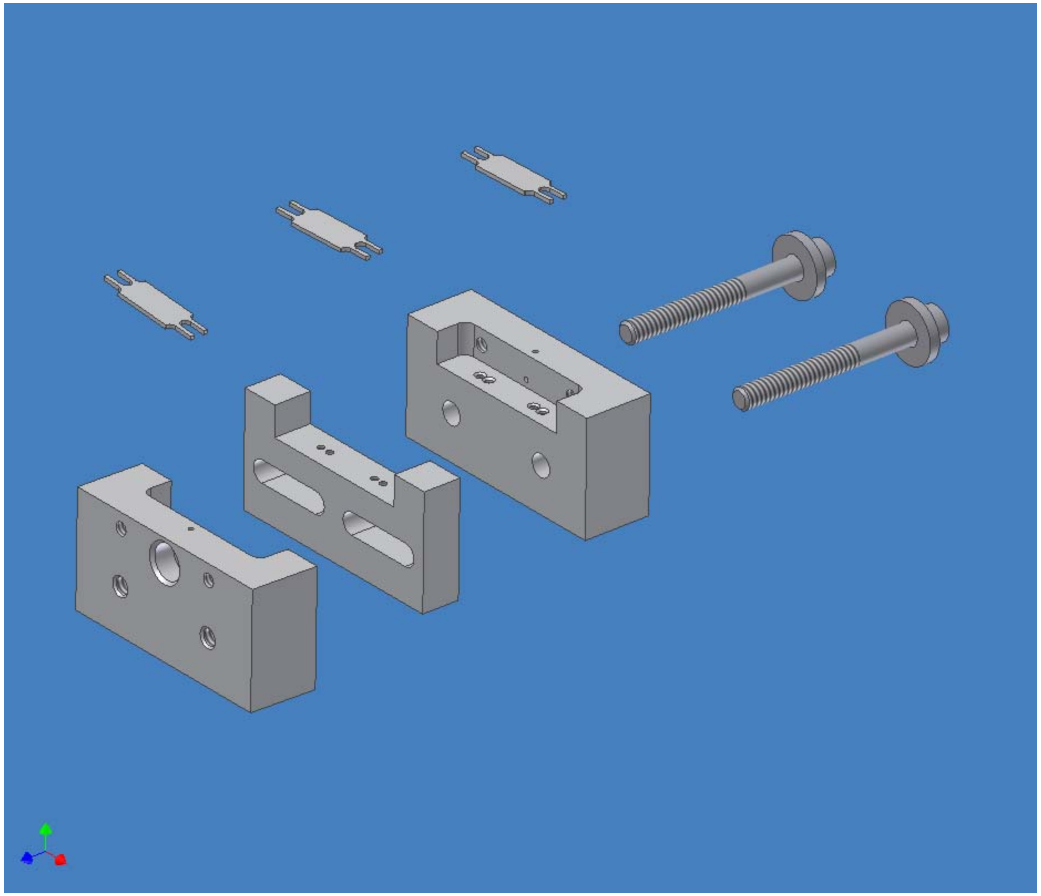
HTS Wafer Artwork

- 3-Inch Diameter



Microstrip Line Loss Measurement

- Fixture



•YBCO/MgO
•Au/alumina

Cost Estimates

- Gold/Alumina

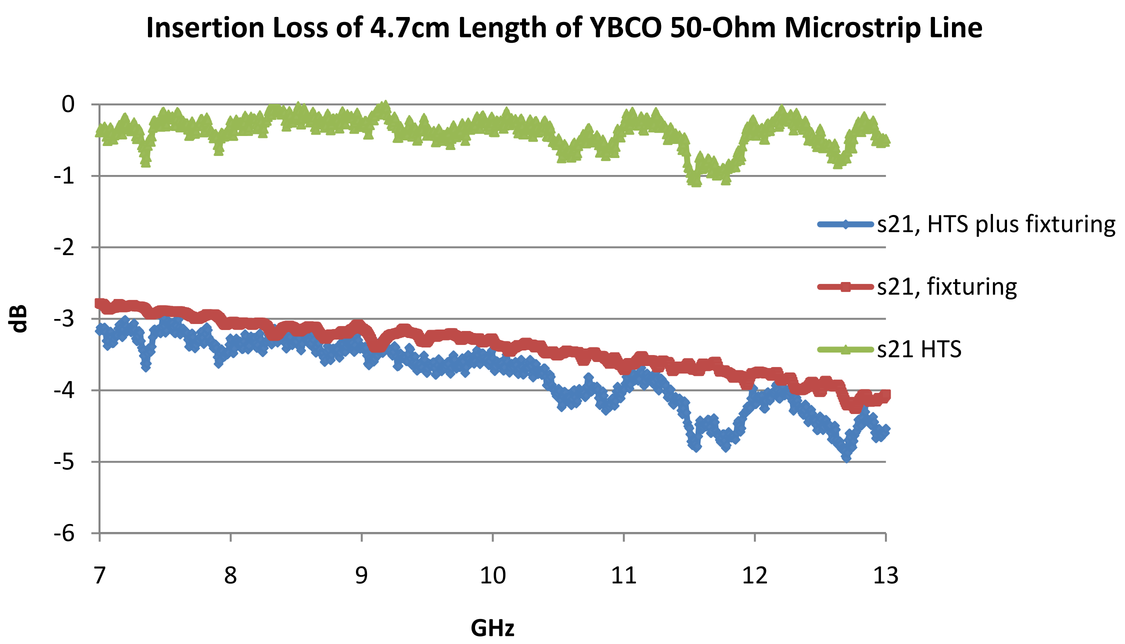
Item	Cost (for small quantities) USD	Cost (for 30+) USD
Microstrip circuits	325.	
Gold plating of chip carriers	Done at NRAO CDL	Done at NRAO CDL
G10 fiberglass	50.	
Brass, aluminum blocks	45.	
Kovar sheet	25.	
Totals	445.	

- YBCO/MgO

Item	Cost (for small quantities) USD	Cost (for 30+) USD
Microstrip circuits	2500.	
Gold plating of chip carriers	600.	Done at NRAO CDL
G10 fiberglass	50.	
Brass, aluminum blocks	45.	
Kovar sheet	25.	
Totals	3220.	

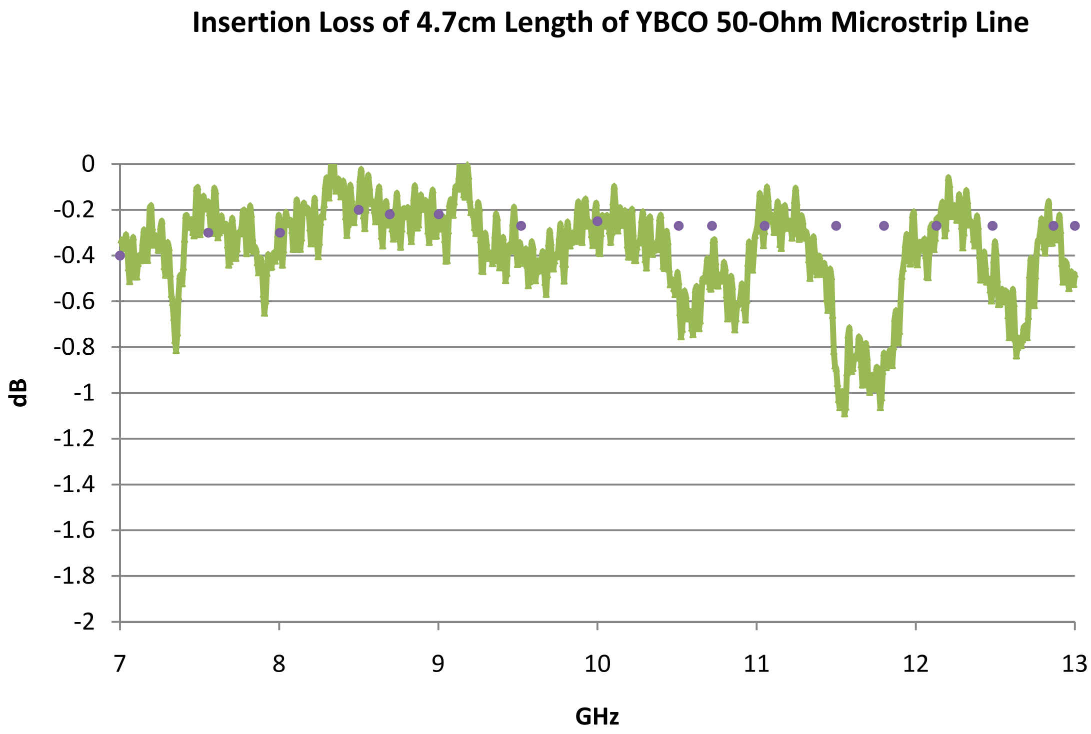
Microstrip Line Loss, T= 15K

- YBCO/MgO, 4.7 cm Length
- 54% of the OMT's Path Length



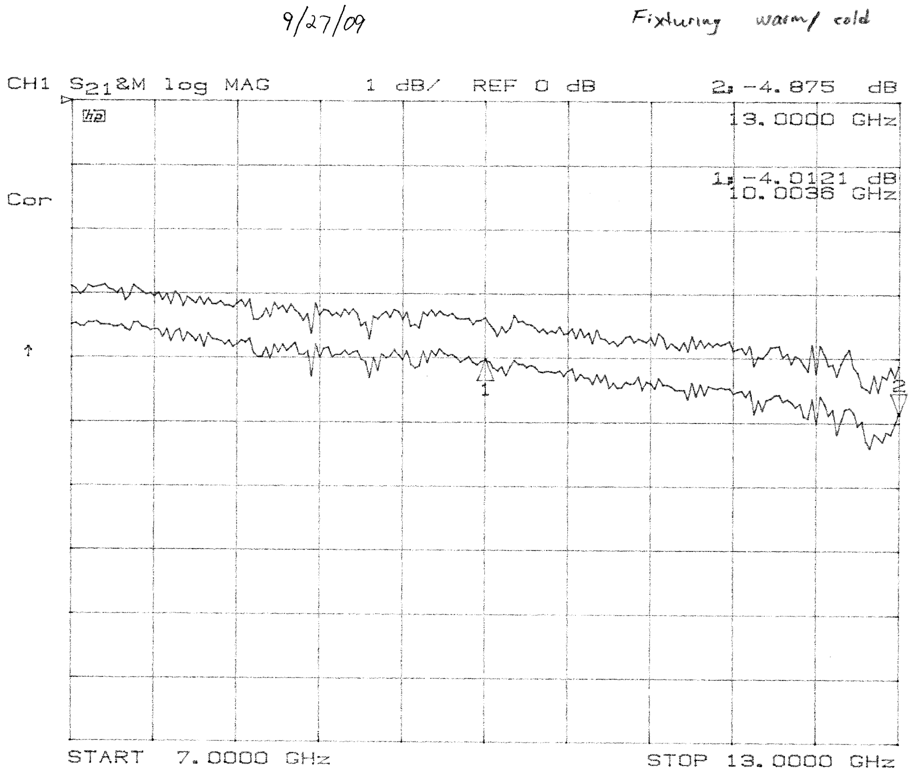
Microstrip Line Loss, T= 15K

- Removing effect of s11



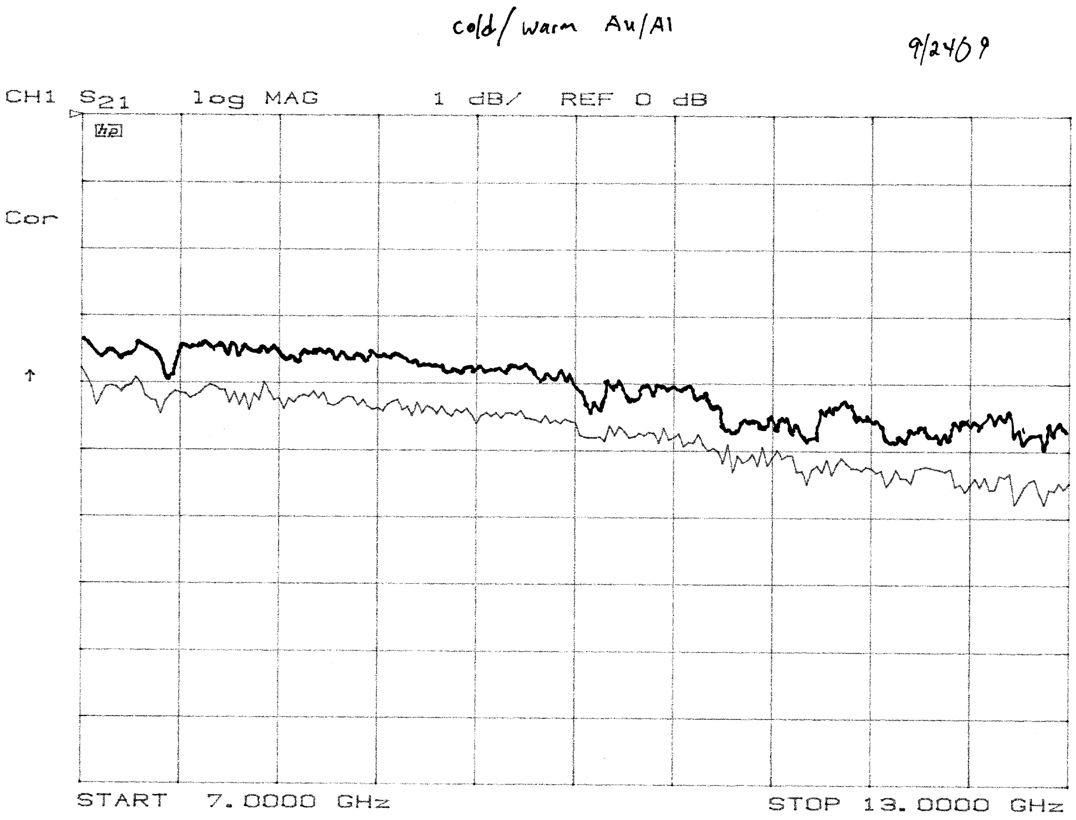
Signal Loss Through Fixturing

- Warm and Cold



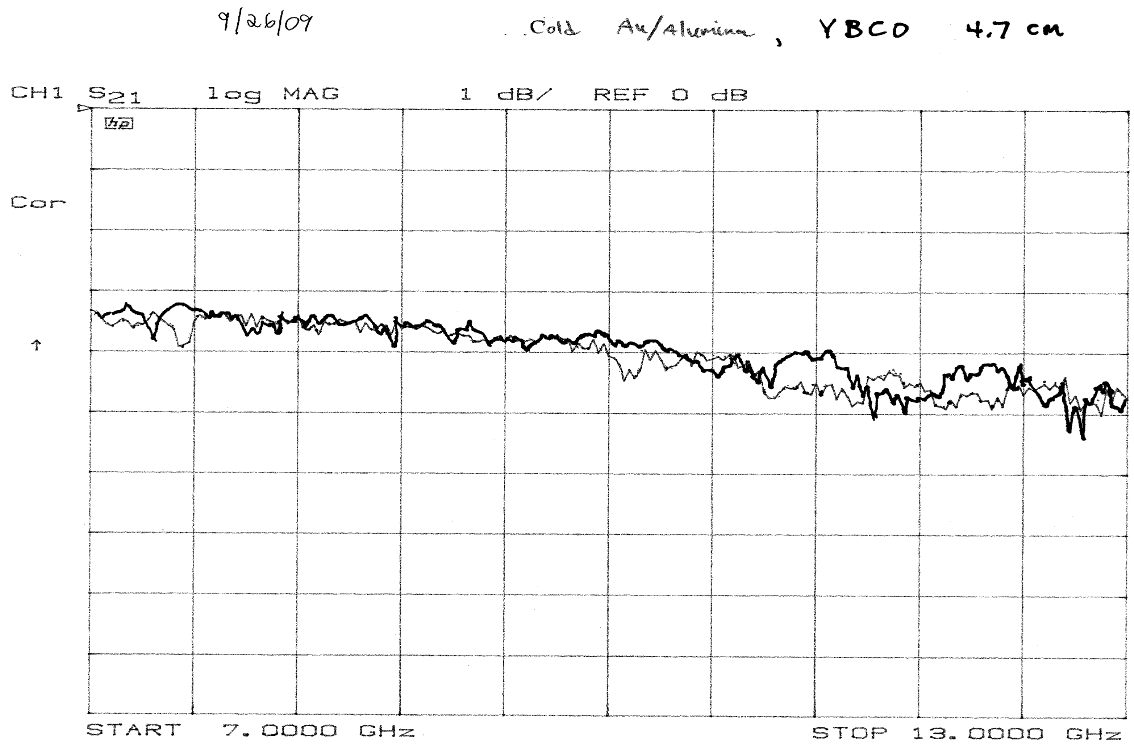
Loss Through Au/Alumina Microstrip

- Warm compared to Cold, Includes Fixture Losses



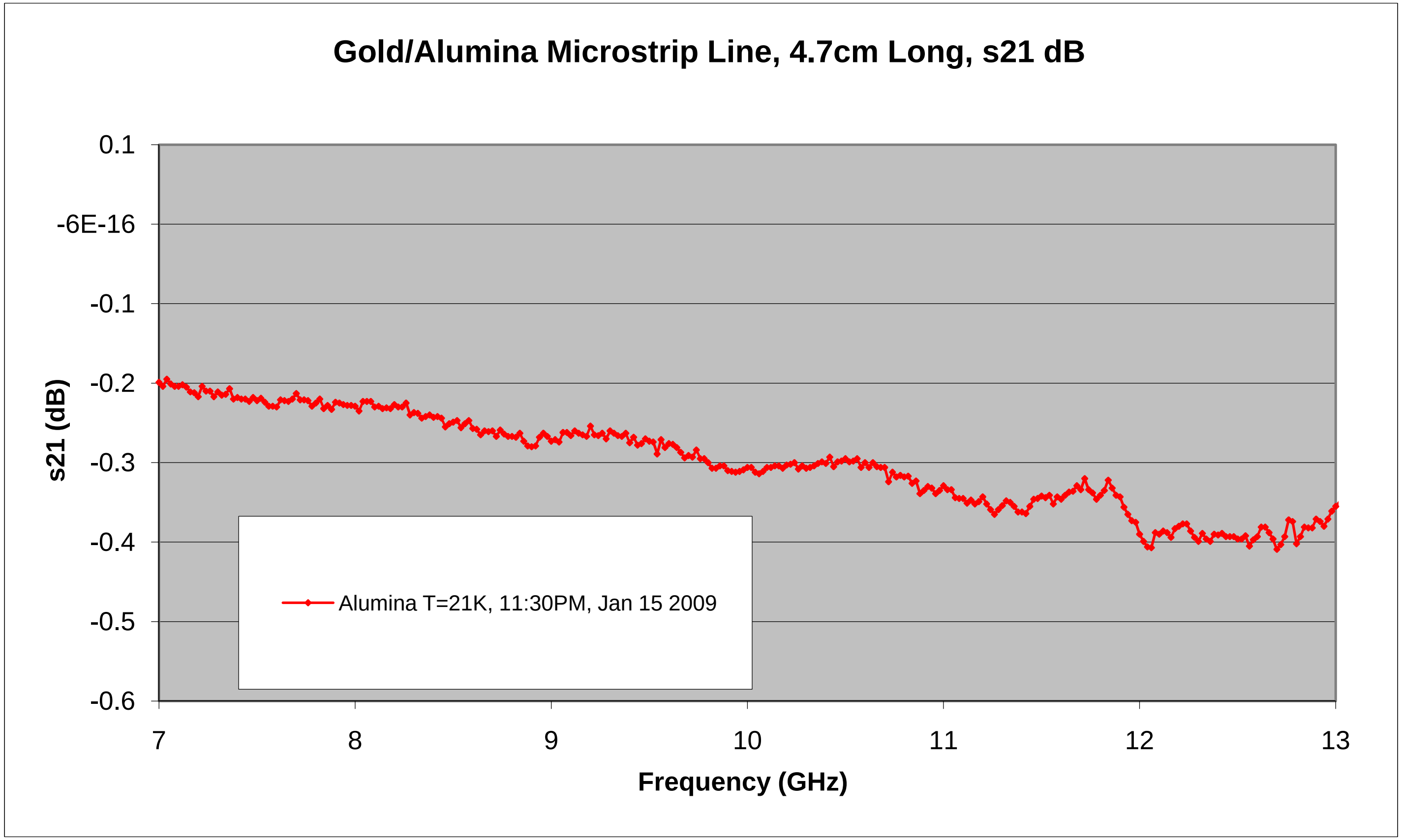
Microstrip Line Loss, Gold vs. YBCO

- Includes Fixture Losses



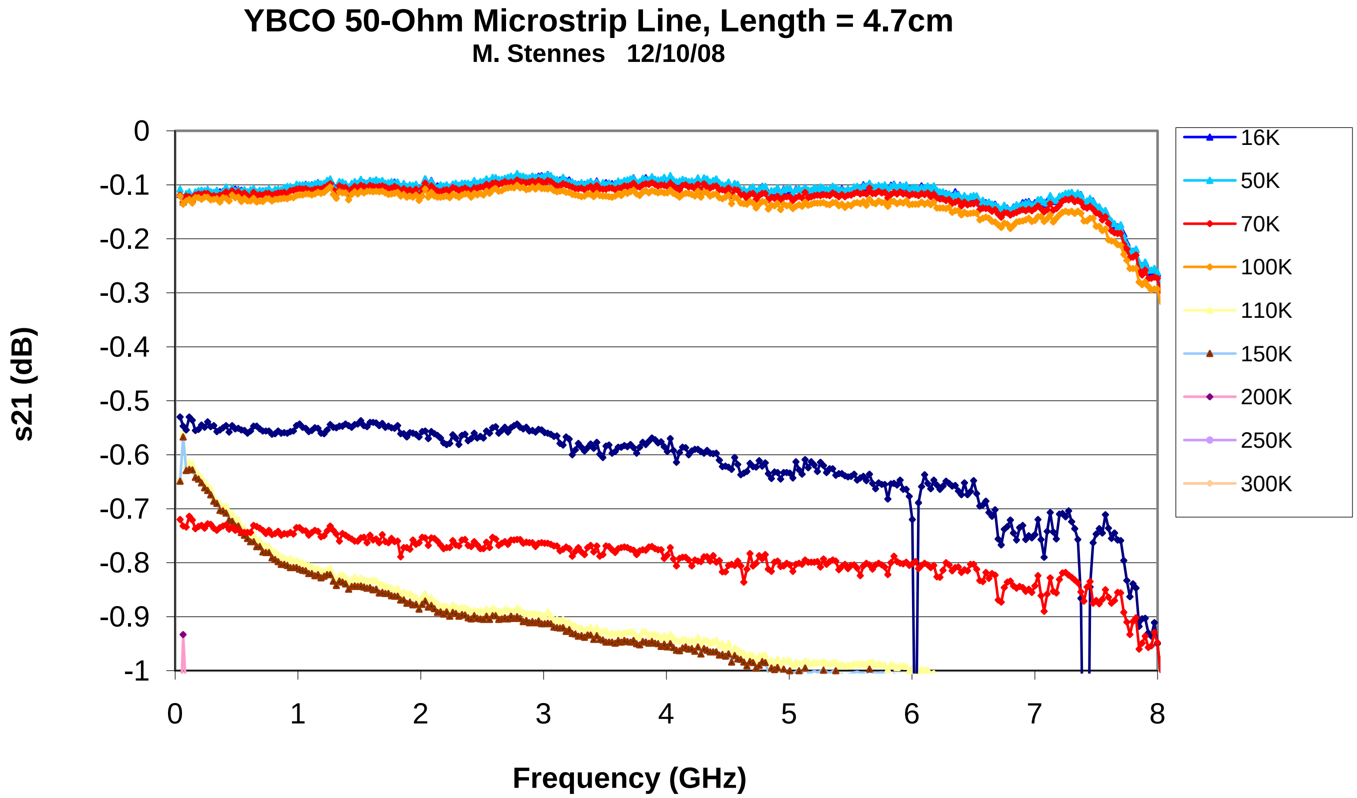
Earlier Loss Measurement: Au/Alumina

- T=15K



Microstrip Line Loss: Gold vs. YBCO

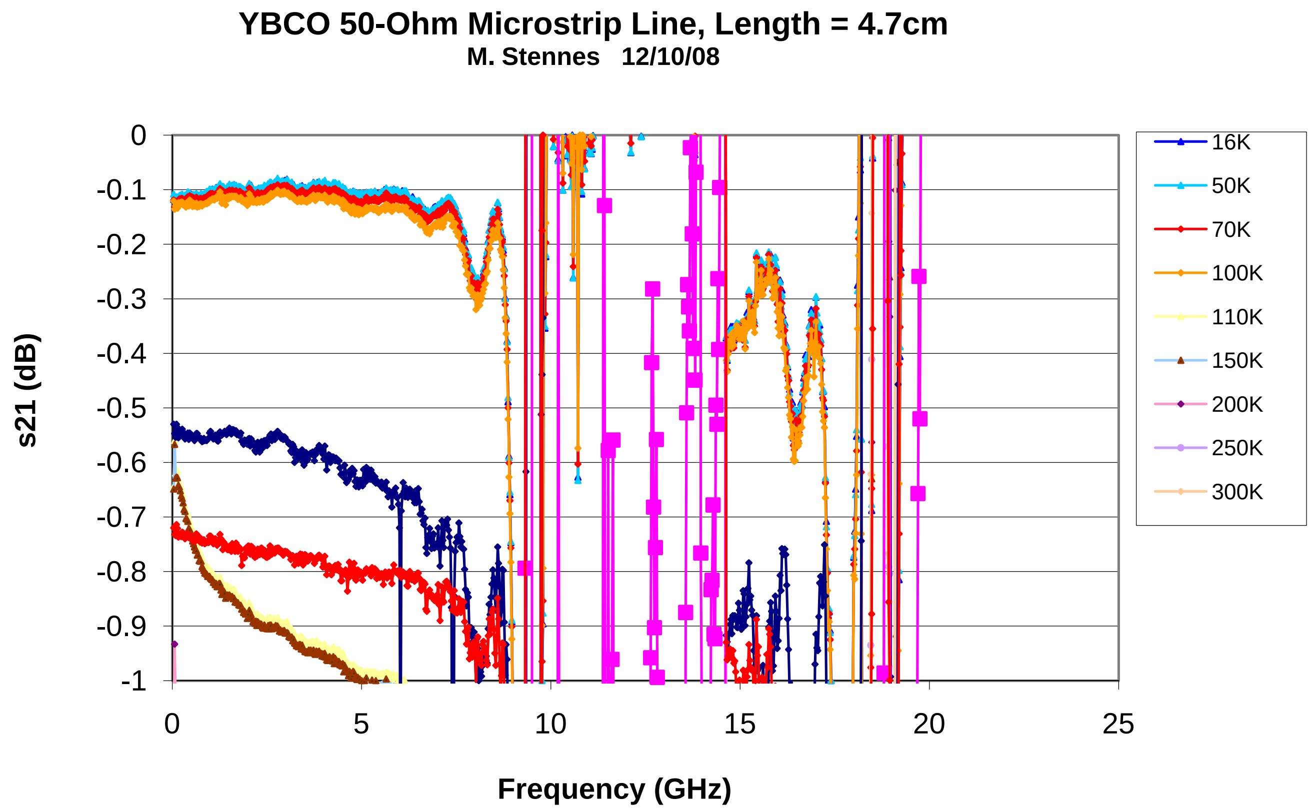
- December 2008



NRAO

Microstrip Line Loss: Gold vs. YBCO

- December 2008



Conclusions

- OMT loss measurements are consistent with receiver noise (Trx) levels
- Receiver noise temperatures of 25K for Gold/Alumina were achieved. Cooled microstrip loss, and other data indicate that Trx = 15K may be possible
- YBCO/MgO OMT may offer lower loss for X-band. 8K to 9K demonstrated over narrow band.
- A significant design flaw was identified; waveguide thermal gap (15K/50K) must be redesigned.
- A lower-loss OMT may be realized, by implementing a single-ended probe design, and/or eliminating the 90-degree hybrid coupler.
- OMT input return loss of -15 dB is predicted, but not demonstrated
- OMT polarization isolation is limited by the microstrip crossovers (-25 dB) and 90-degree hybrid (-19 dB)

Possible Improvements

- Reduce OMT loss by:
  - elimination of wire bonds
  - Full closure of 15/50K thermal gap
- Improve OMT isolation by optimizing microstrip crossover design, and by providing amplitude and phase predistortion to compensate for 90-degree hybrid's finite isolation (-19 dB)
- Use single-ended waveguide probe, eliminate 180-degree hybrid
- Reduce receiver noise temperature with use of integrated MMIC LNA
- Improve OMT return loss through:
  - Linear system modeling and fixed tuning
  - Variable tuning with real-time s11 measurement
  - Wafer probing and fixed tuning

Possible Improvements (continued)

- Total elimination of the 15K/50K thermal gap, having just one gap for 15K/300K.