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200 GHz Low Noise Amplifiers in 250 nm InP HBT Technology

Utku Soylu

Affiliation: ECE, University of California, Santa Barbara, USA

Email address: utkusoylu@ucsb.edu

A. S. H. Ahmed[1], M. Seo[2], A. Farid[1], M. Rodwell[1]

[1]ECE, University of California, Santa Barbara, USA

[2]ECE, Sungkyunkwan University, South Korea

Outline

- Motivation
- Amplifier design
  - Noise measure technique
  - Low-loss input matching
- Measurement results
- Application of the amplifier
- Summary

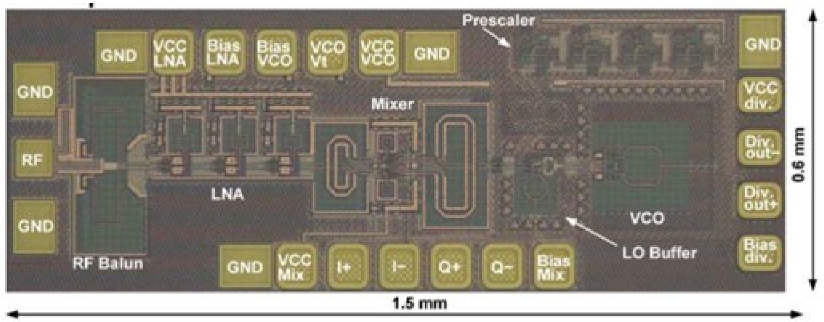
Motivation

- Increasing interest in the 200-300 GHz:

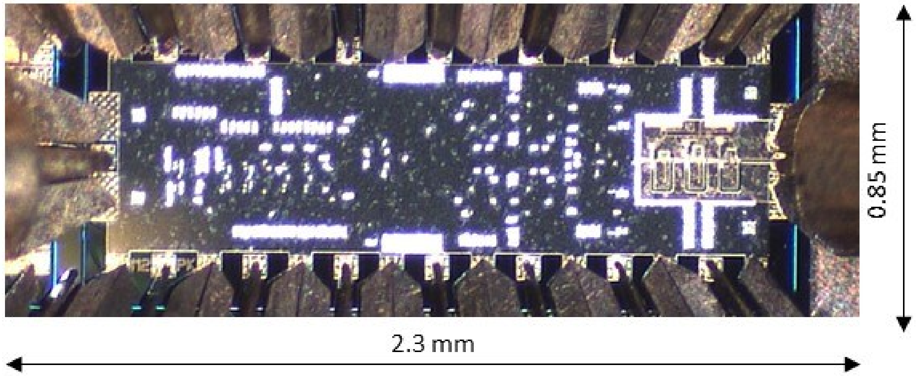
  Large available BW → High data rate
- Greater integration scales in SiGe/InP HBT receivers than in III-V HEMT technologies
- More competitive 200-300 GHz all-HBT Rx with reduced HBT LNA noise figure
- Ideal Case:

  Hybrid Rx with HEMT LNA + HBT post-LNA

160 GHz Rx in SiGe HBT [2]

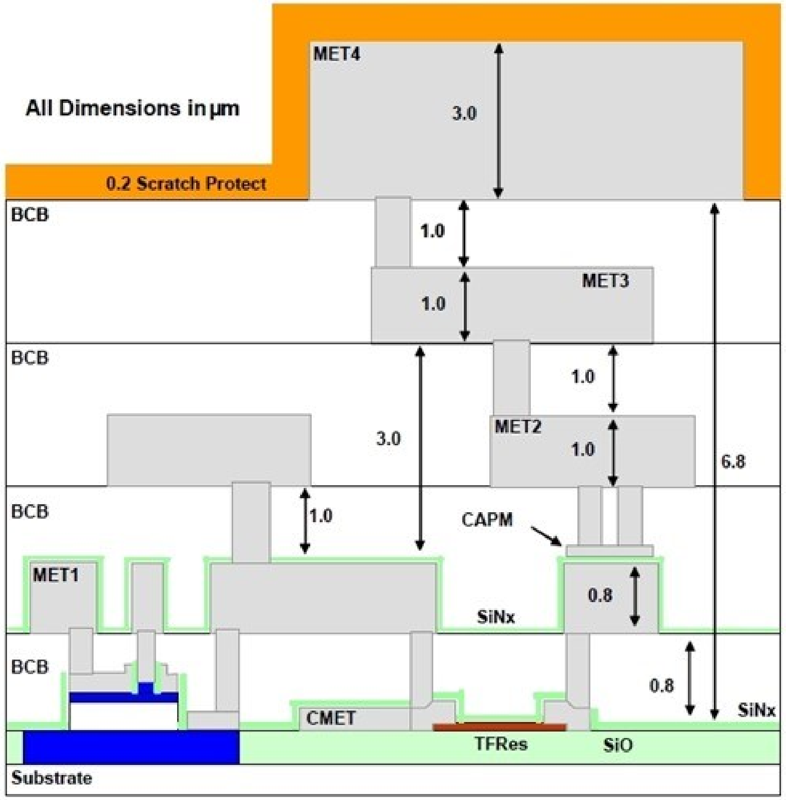


200 GHz Rx in InP HBT [14]



250 nm InP HBT Process (Teledyne [1])

- Four Au interconnect.
- TFR (50Ω/square).
- MIM cap (0.3fF/µm2).
- f_{max}=650GHz.
- J_{max}=3mA/µm.
- BV_{CEo}=4.5V.
- MET4 = Signal, MET1 = GND
- Loss of MSL = 1.1 dB/mm @ 200 GHz
- Loss of inv-MSL = 2.5 dB/mm @ 200 GHz

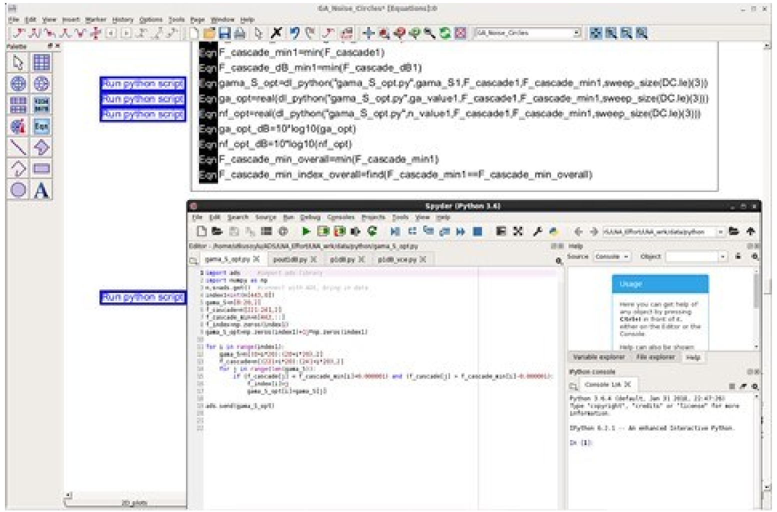


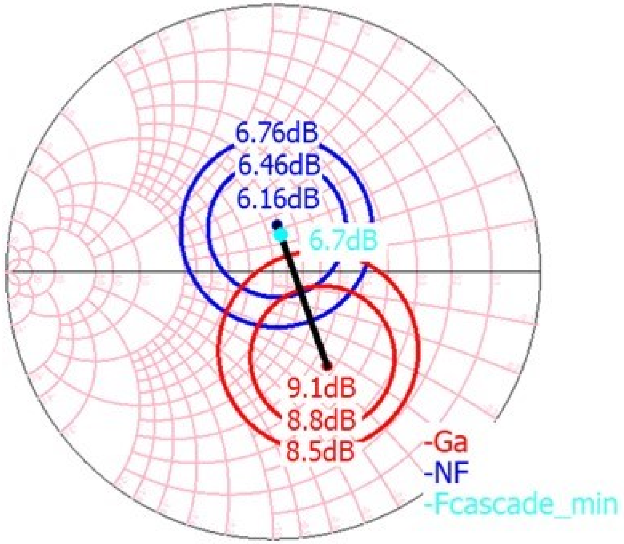
Representative cross-section of TSC250 IC technology. Drawing is not to scale.

Cross Section of TSC250 IC

Noise Measure

$$F_{\text{cascade}} = M + 1 = F + \frac{F-1}{G} + \frac{F-1}{G^2} + \cdots = \frac{F - G^{-1}}{1 - G^{-1}} \rightarrow M = \frac{F-1}{1-G^{-1}}$$





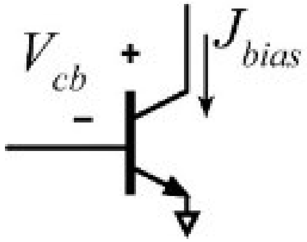
Minimum Noise Measure Impedance:

1. Draw a line between centers of NF and Ga Circles.
2. Calculate M for each point on this line.
3. Determine the point on the line having the *smallest* M

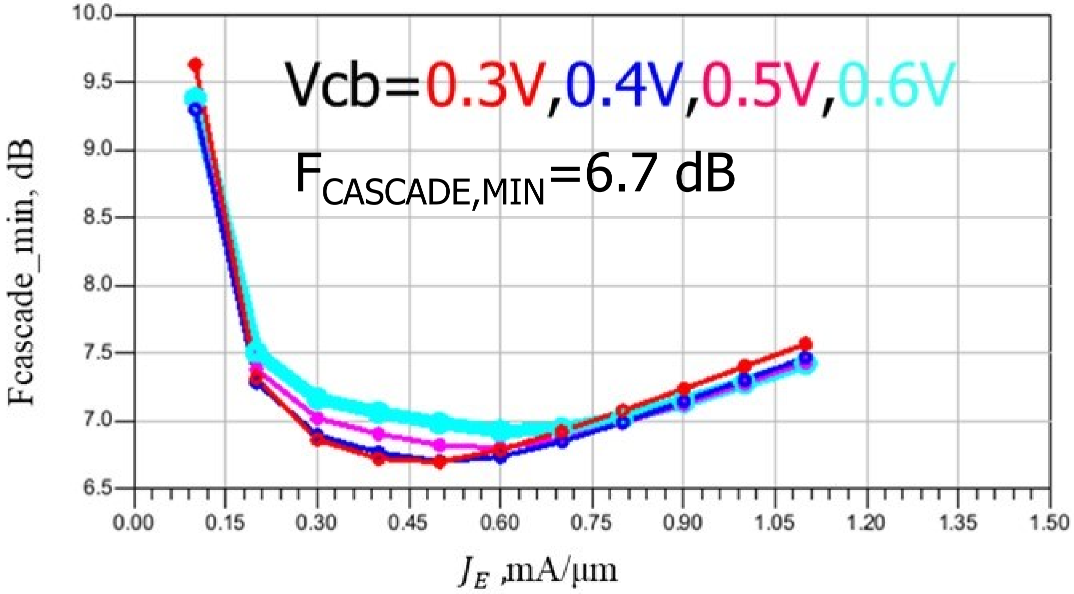
Data is for an (0.25 x 5 µm^2) HBT in CB configuration with 200 fF base capacitance biased at VCB=0.4 V and JE=0.5 mA/µm

[14] H. Fukui, "Available Power Gain, Noise Figure, and Noise Measure of Two-Ports and Their Graphical Representations," in IEEE Transactions on Circuit Theory, vol. 13, no. 2, pp. 137-142, June 1966.

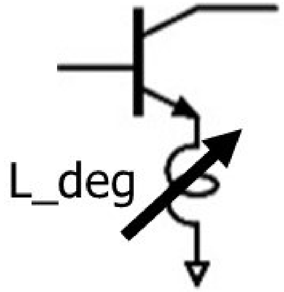
Determining Bias Condition

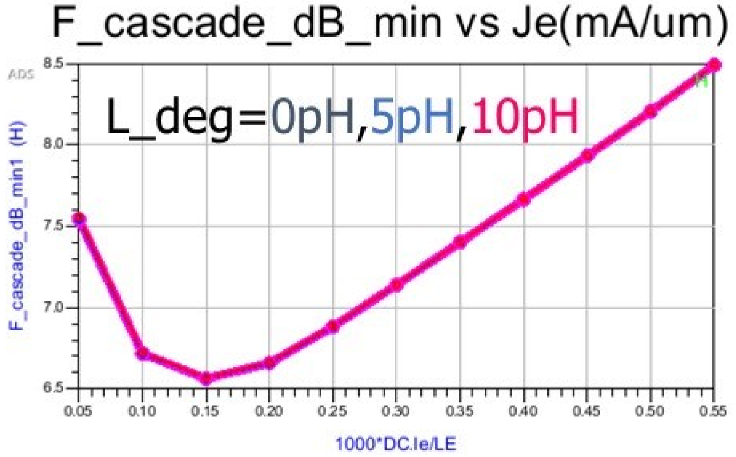


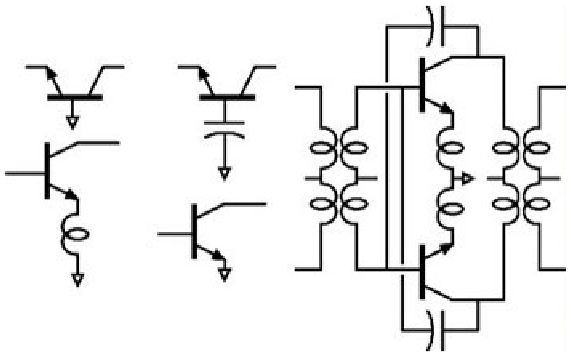
$F_{CASCADE,MIN}$ as a function of emitter current density (J_E) and collector-base voltage (V_{CB}) for a 0.25 µm x 5 µm HBT.



Noise Measure as a 2-port Invariant





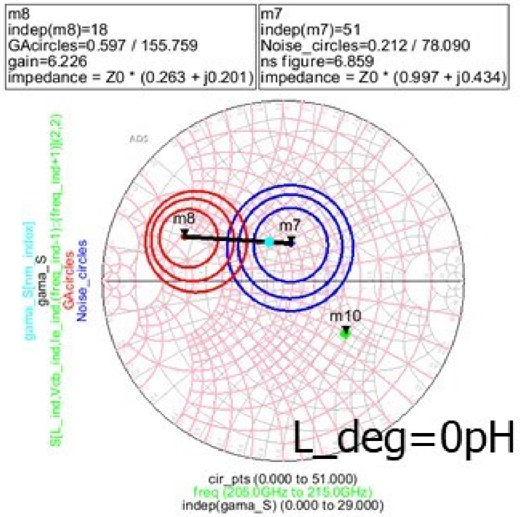


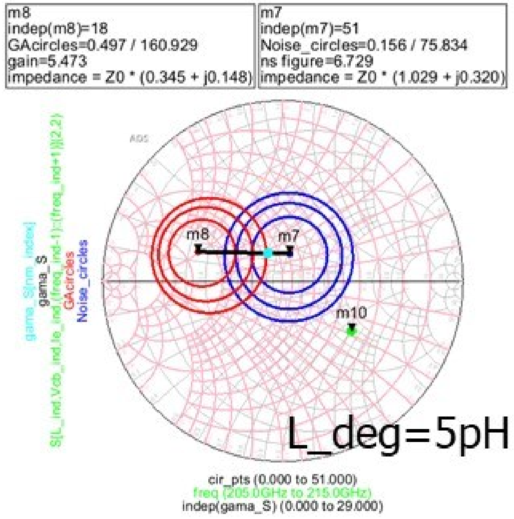
Base Capacitance in CB

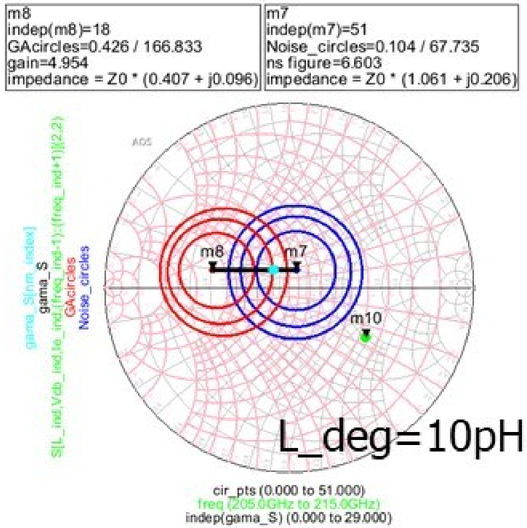
↕

Emitter Inductance in CE

[10] H. A. Haus and R. B. Adler, "Optimum Noise Performance of Linear Amplifiers," in Proceedings of the IRE, vol. 46, no. 8, pp. 1517-1533, Aug. 1958.







Minimum M is independent of circuit configuration;

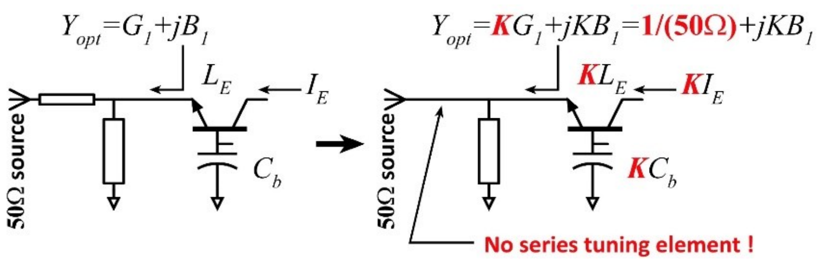
Pick for high bandwidth or high gain/stage (=low P_{DC})

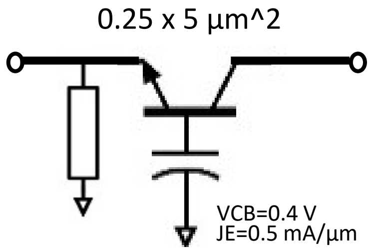
Data is for an (0.25 x 3 µm^2) HBT in CE configuration biased at VCB=0.4 V and JE=0.5 mA/µm

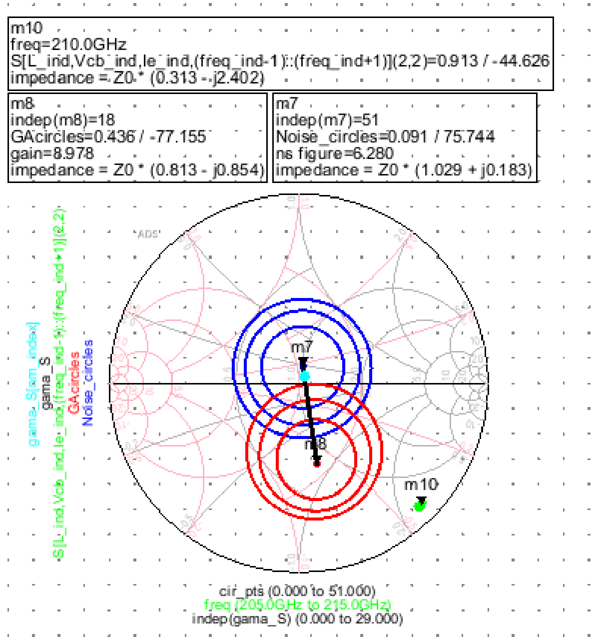
Input/Output Matching Matching

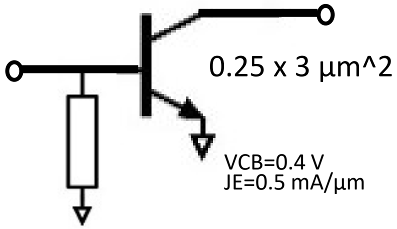
$$F_{\text{cascade}} = F + \frac{F-1}{G} + \frac{F-1}{G^2} + \cdots = \frac{F-G^{-1}}{1-G^{-1}}$$

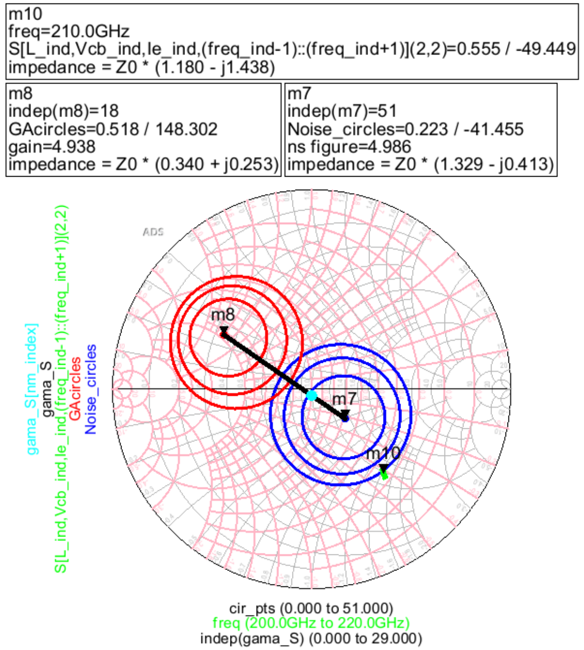
$$F_{\text{cascade}} = F_{\text{input\_match}} + F_{\text{t}} + \frac{F_{\text{output\_match}} - 1}{G_{\text{t}}} + \cdots = \frac{F-G^{-1}}{1-G_{\text{t}}^{-1}}$$



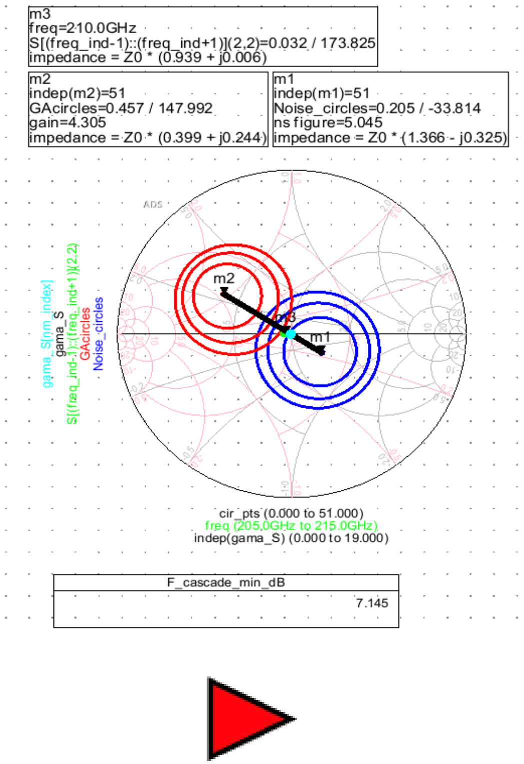




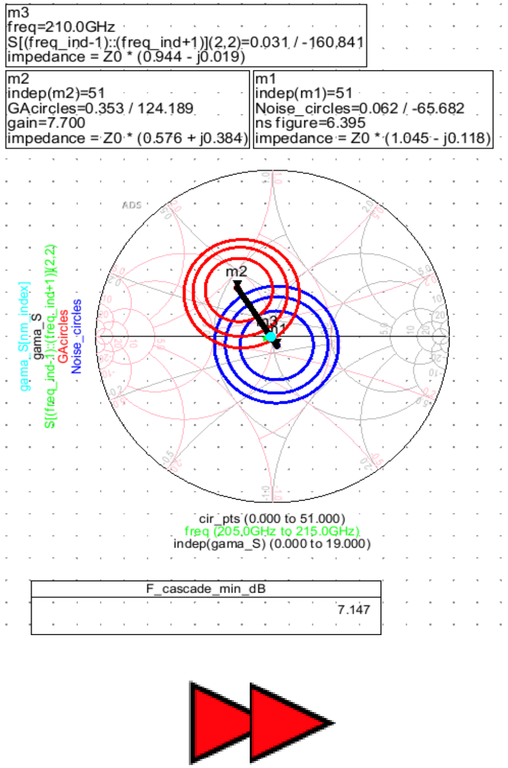




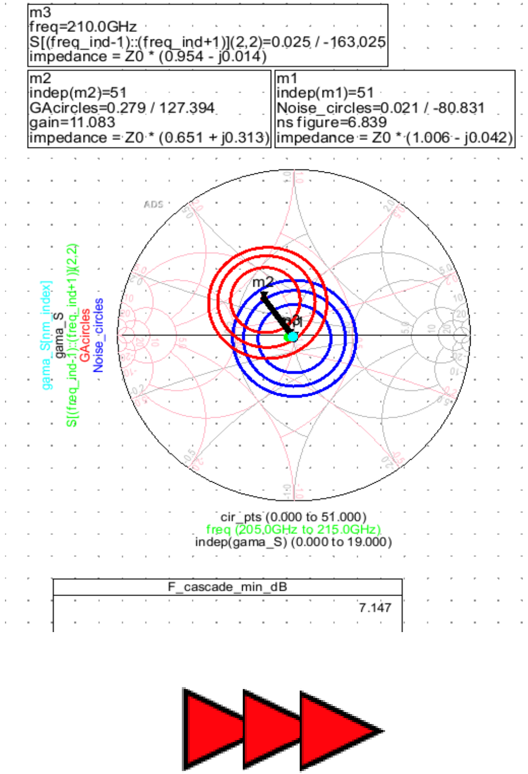
Cascading



1 stage, CE



2 stage, CE

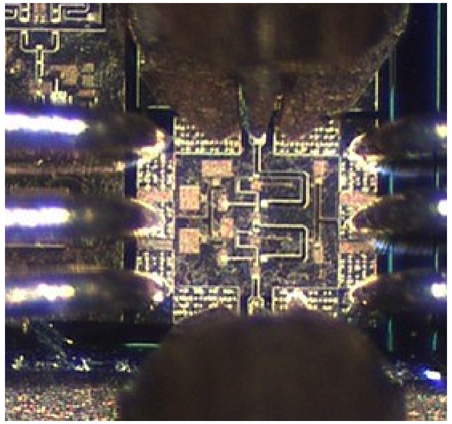


3 stage, CE

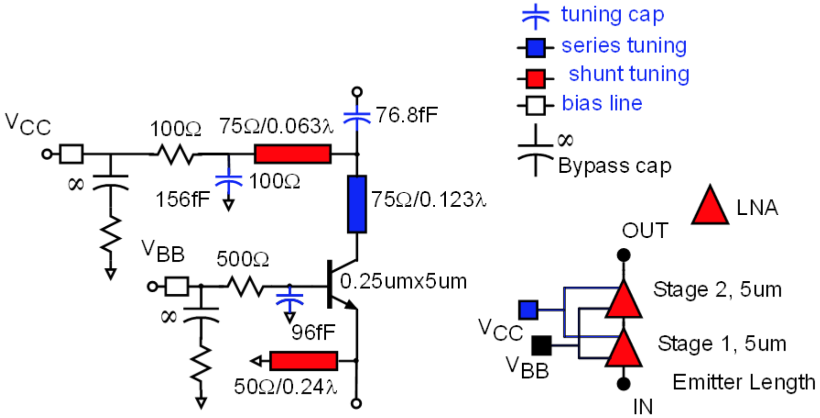
As we cascade more stages:

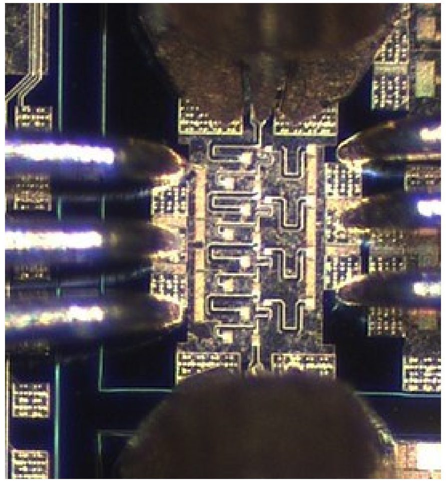
1. NF_{MIN} converges to $F_{CASCADE}$
2. Minimum NF impedance converges to *Minimum NM impedance*

CB and CE Low Noise Amplifiers

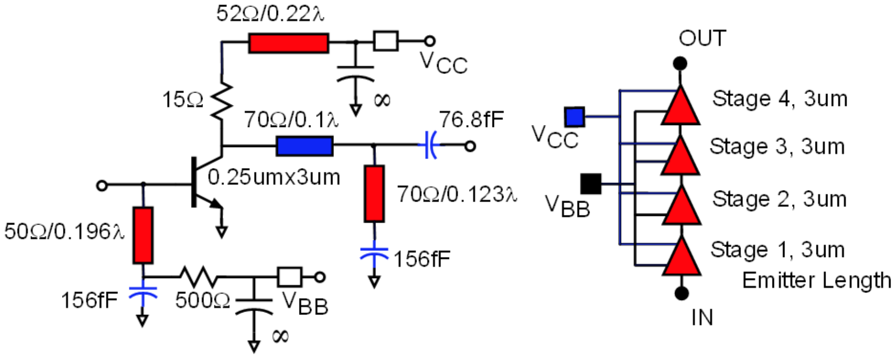


200GHz	CB, 5um, 2 stage
Gain	14.5 dB
BW	33 GHz
NF	7.4 dB
$P_{1dB,in}$	-21.1 dBm
P_{DC}	9.2 mW
Die Area	290umx245um
$J_{emitter}$ V_{cb}	0.6mA/um 0.4V

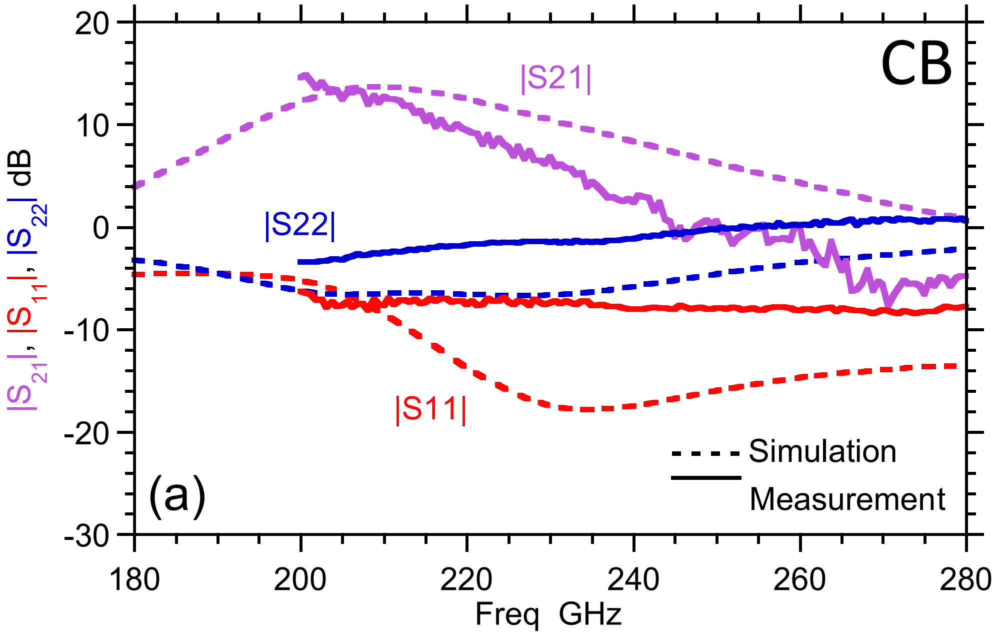


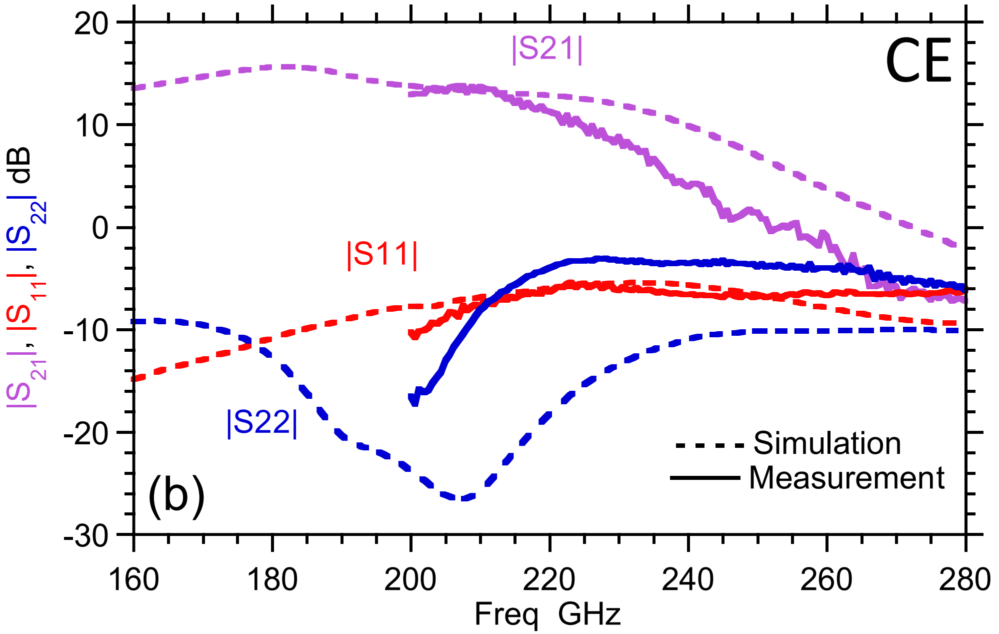


200GHz	CE, 5um, 4 stage
Gain	13 dB
BW	60 GHz
NF	7.2 dB
$P_{1dB,in}$	-18.2 dBm
P_{DC}	19.22 mW
Die Area	290umx465um
$J_{emitter}$ V_{cb}	1.0mA/um 0.56V



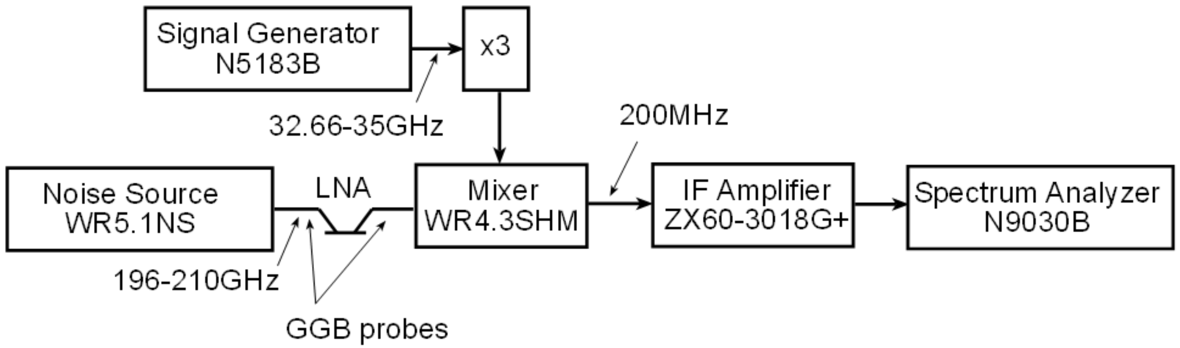
Measurement Results: S-parameters

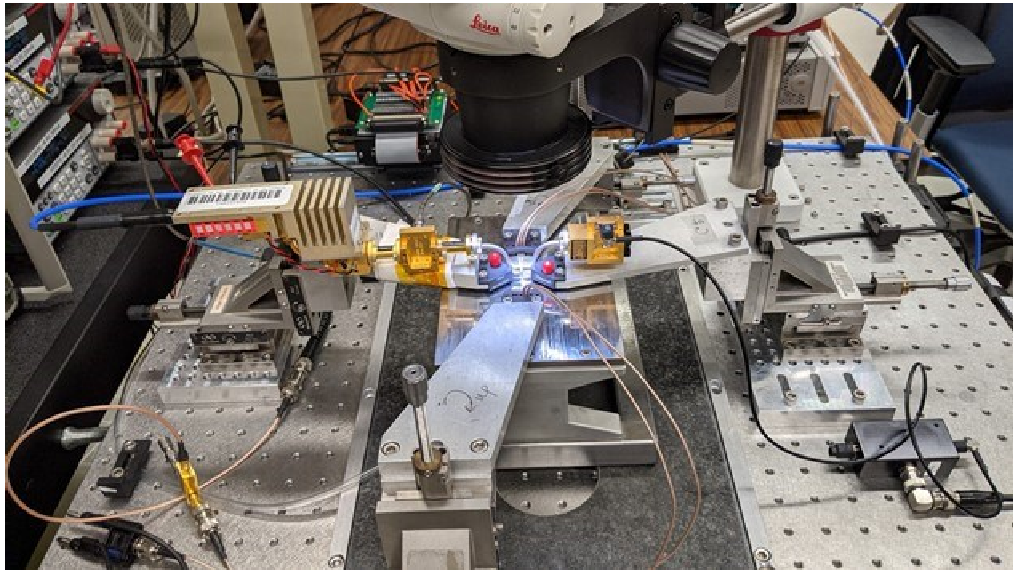




- WR-03 frequency extenders and probes, SOLT calibration
- 5 % frequency down-shift
- Good agreement between peak simulated and measured gain

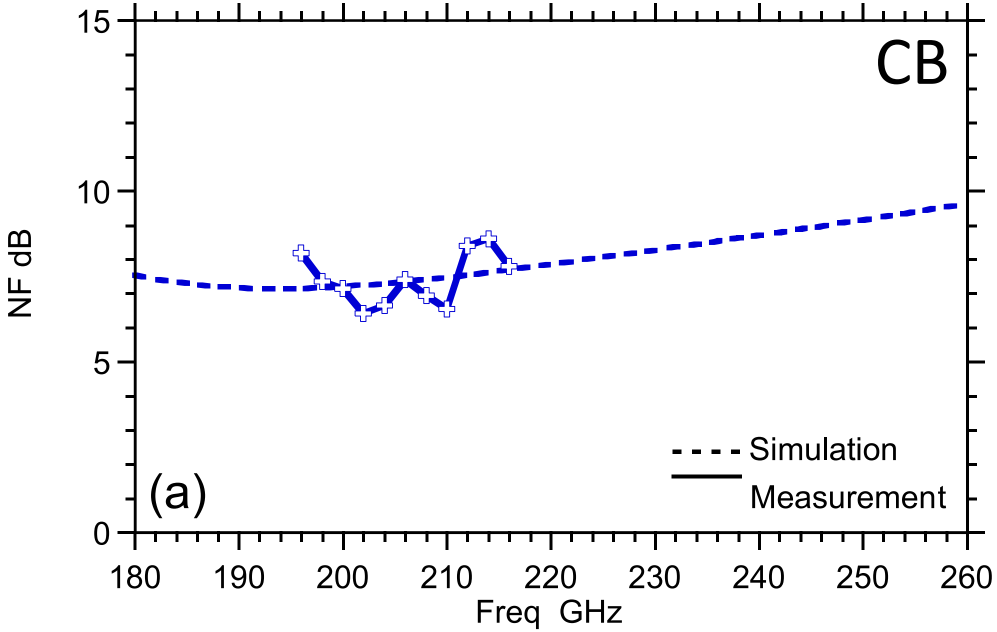
Setup: Noise Measurement



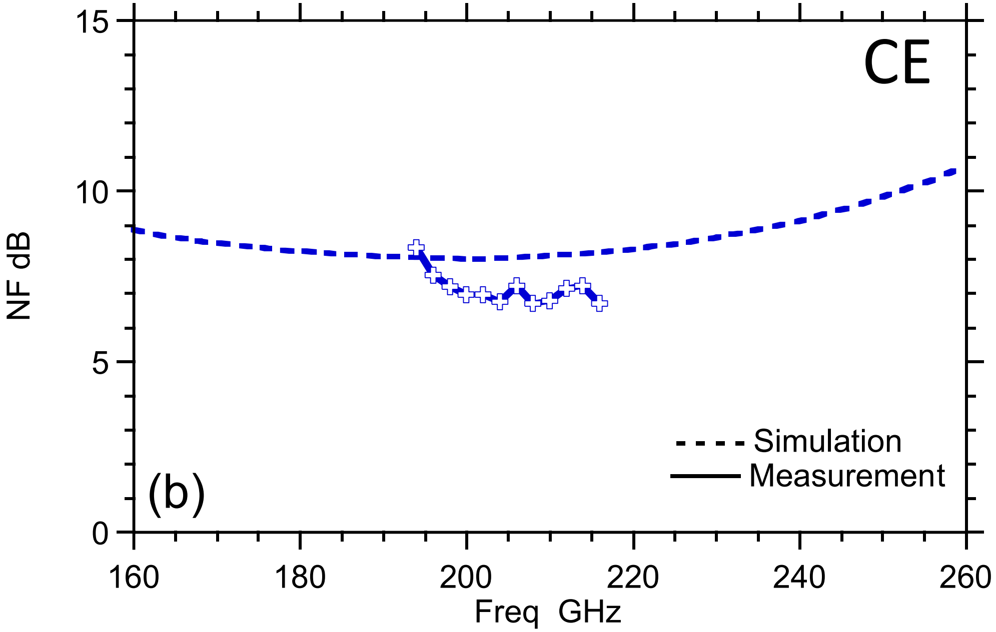


- Hot/Cold Y-parameter method (VDI-WR5.1NS noise source)
- The probe loss (2.0 dB @ 200 GHz) and is deembedded from NF
- ~20 dB BB LNA used to reduce noise contribution from SA

Measurement Results: Noise Figure

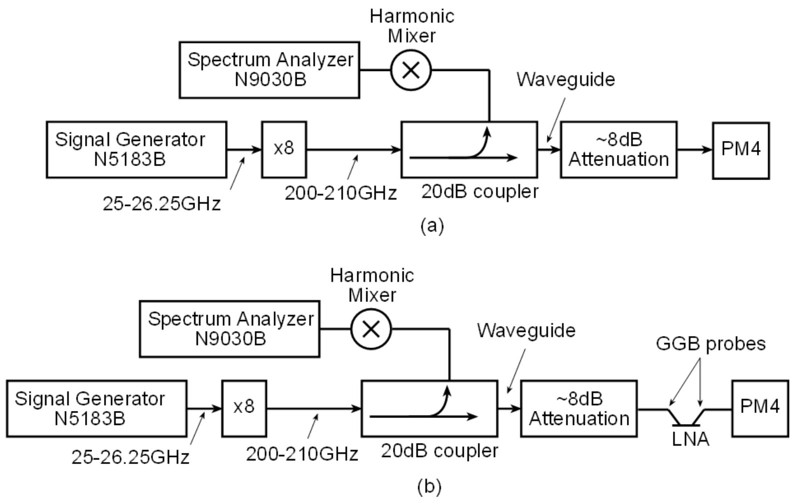


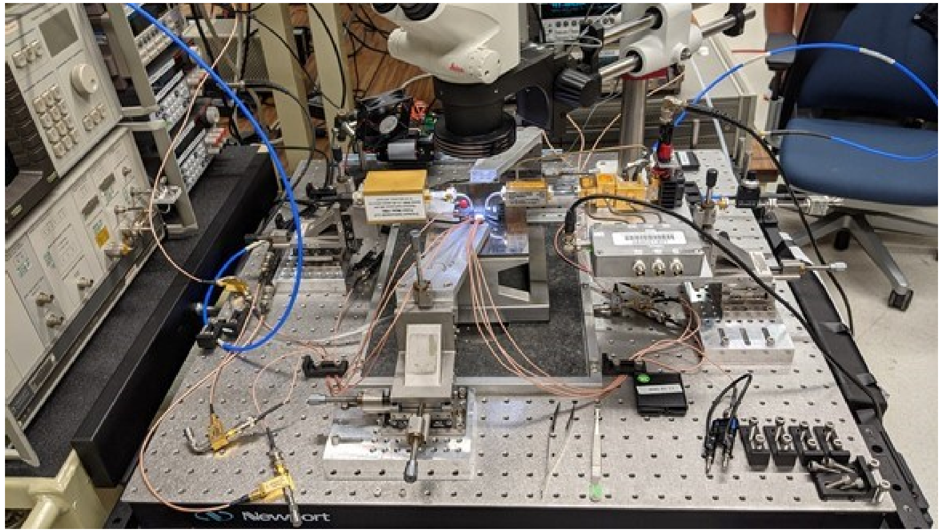
- CB: 7.4±0.7 dB noise figure over 196-216 GHz



- CE: 7.2±0.4 dB noise figure over 196-216 GHz

Setup: Power Measurement

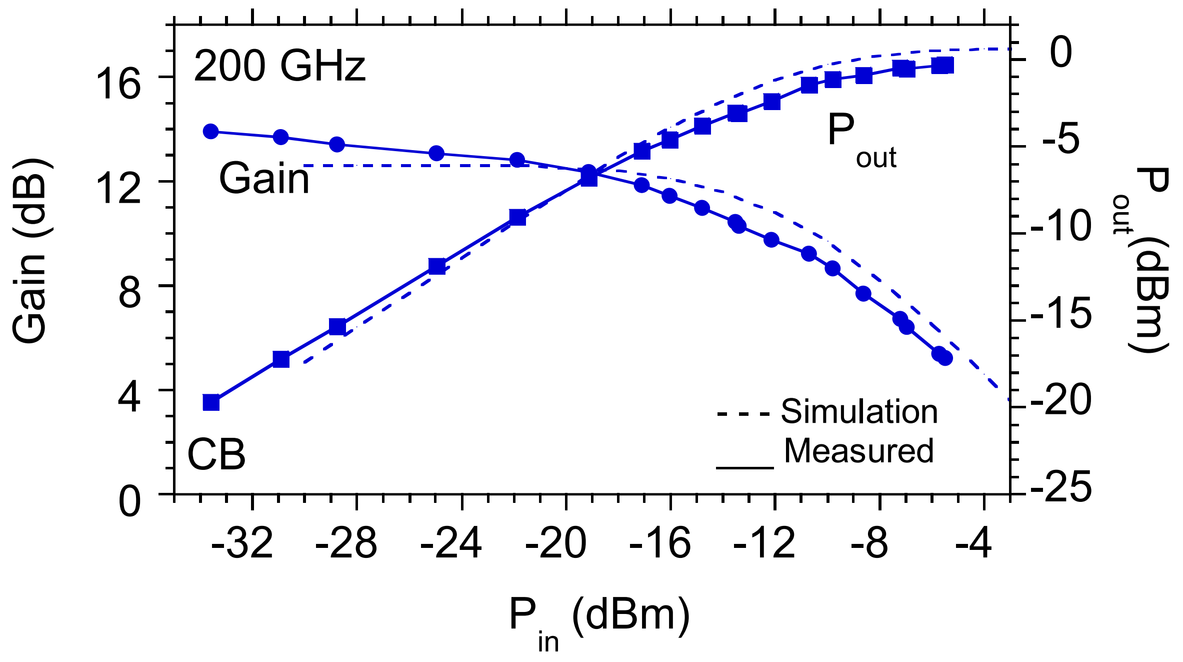


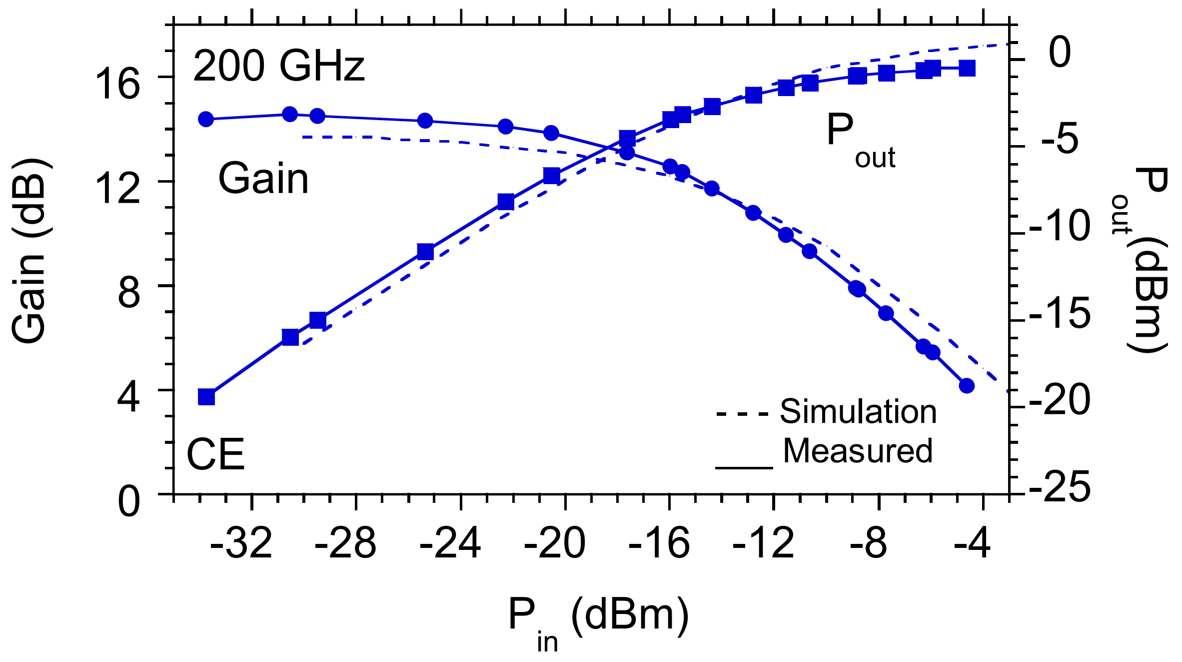


- Simultaneous input and output power measurement
- Accurate gain measurement even at low input power
- All measurements are done without lifting the probes

[13] A. S. H. Ahmed, U. Soylu, M. Seo, M. Urteaga, J. F. Buckwalter and M. J. W. Rodwell., " A 190-210GHz Power Amplifier with 17.7-18.5dBm Output Power and 6.9-8.5% PAE.," in press, Proc. IMS2021.

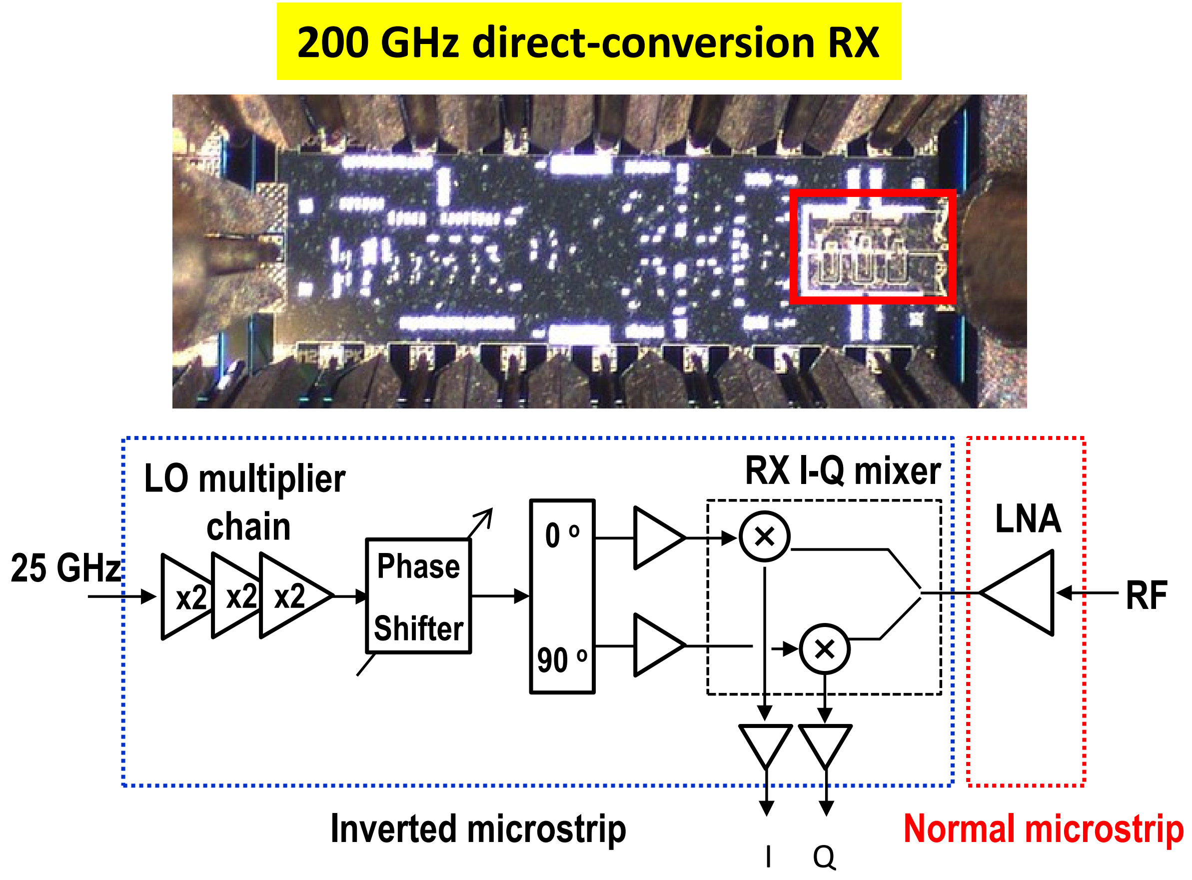
Measurement Results: Power





- CB: -21.1 dBm Pin1dB @ 200 GHz
- CE: -18.2 dBm Pin1dB @ 200 GHz

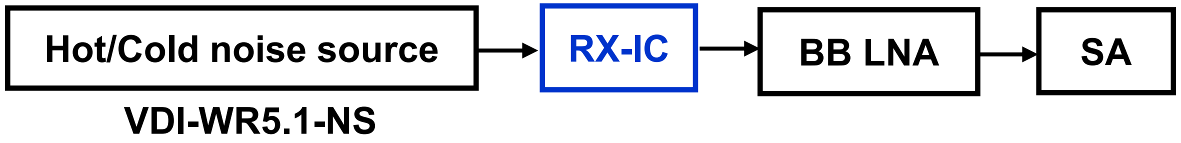
Receiver with Staggered Tuned CB LNA

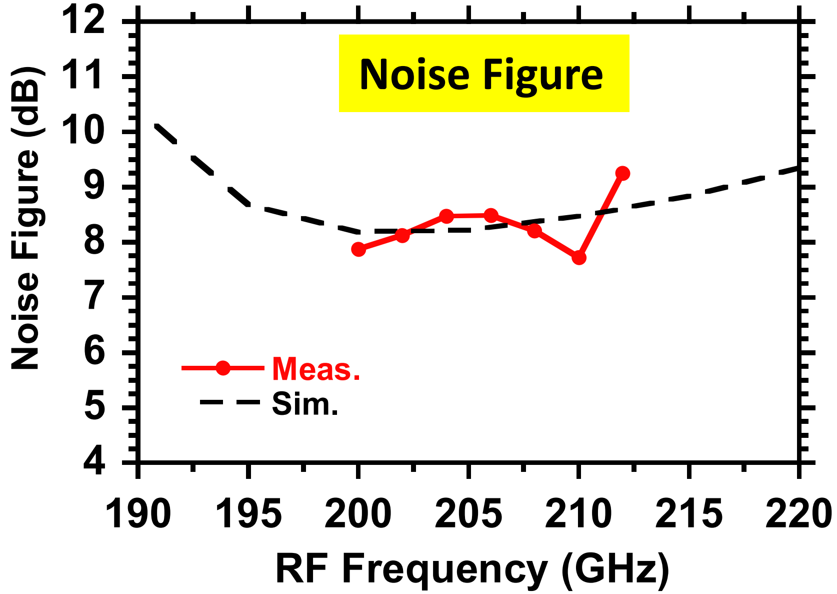


- LNA: Normal microstrip for lowest NF
- Mixer, LO multiplier, phase shifter: Inverted microstrip for low-inductance ground
- 3-stage staggered tuned CB LNA to increase 3 dB modulation bandwidth of the receiver

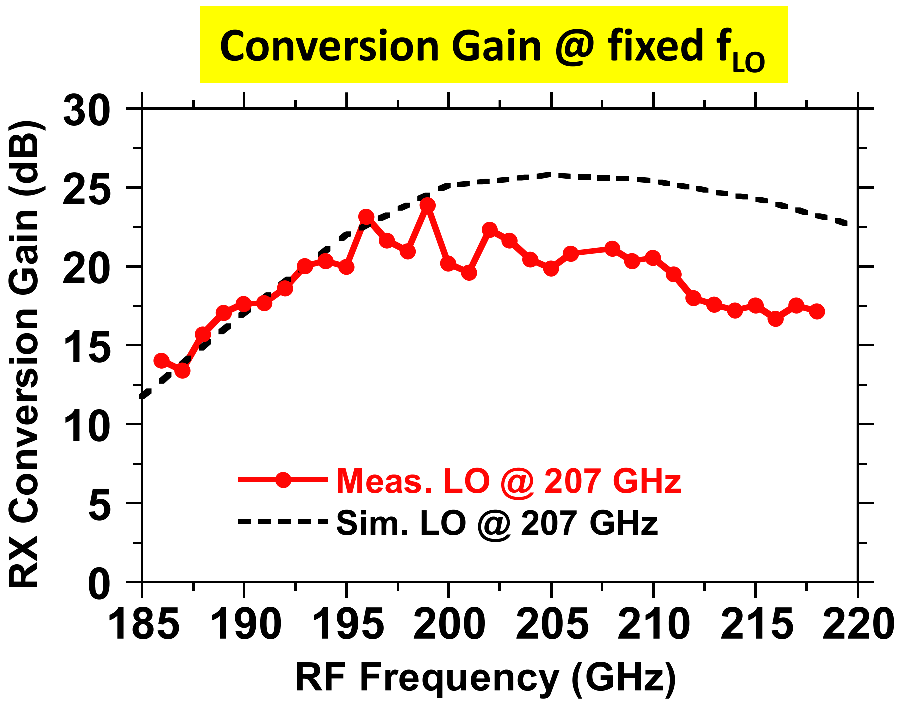
[14] M. Seo, A. S. H. Ahmed, U. Soylu, A. Farid, Y. Na and M. Rodwell, "A 200 GHz InP HBT Direct-Conversion LO-Phase-Shifted Transmitter/Receiver with 15 dBm Output Power," 2021 IEEE MTT-S International Microwave Symposium (IMS), 2021.

Measured Rx NF and Conversion Gain





$F_{CASCADE}$	
5 um device	**6.7 dB**
1-stage LNA	**7.5 dB**
NF of Rx	**8.5-8.8 dB**



- Peak conversion gain = 22 dB

Performance Comparison

Table 1. Comparison of recently published >150 GHz low noise amplifiers

Ref.	Technology	Topology	Freq (GHz)	Gain (dB)	Gain/stage (dB)	NF (dB)	P_{DC} (mW)
[2]	250 nm SiGe HBT	Cascode, diff. mode	156	26	8.7	8.5	-
[3]	50 nm mHEMT	CS	178-185	24.5	4.9	3.5	24
[4]	50 nm mHEMT	CS	206	16	4.0	4.8	-
[5]	32 nm CMOS	CS	200-220	10-18	1.4-2.6	11	44.5
[6]	130 nm Sige HBT	Cascode, diff. mode	220	18	6	16	151.2
[8]	250 nm InP HBT	CE	265	24	4.8	10	81.7
[9]	250 nm InP HBT	Cascode	288	8.4	8.4	11.2 at 300 GHz	-
This work	**250 nm InP HBT**	CE	200	13	3.25	7.2	19.22
		CB	200	14.5	7.25	7.4	9.2

- This work shows record Noise Figure in HBT technology.

Acknowledgement

- This work was supported by ComSenTer, a JUMP program sponsored by the Semiconductor Research Corporation.

- The authors thank Teledyne Scientific & Imaging for the IC fabrication.

Thank You!

References

- [1] M. J. W. Rodwell et al., “100-340GHz Systems: Transistors and Applications,” in Proc. IEEE IEDM, 2018, pp. 14.3.1-14.3.4
- [2] Y. Zhao, E. Ojefors, K. Aufinger, T. F. Meister and U. R. Pfeiffer, "A 160-GHz Subharmonic Transmitter and Receiver Chipset in an SiGe HBT Technology," in IEEE Transactions on Microwave Theory and Techniques, vol. 60, no. 10, pp. 3286-3299, Oct. 2012.
- [3] G. Moschetti et al., "A 183 GHz Metamorphic HEMT Low-Noise Amplifier With 3.5 dB Noise Figure," in IEEE Microwave and Wireless Components Letters, vol. 25, no. 9, pp. 618-620, Sept. 2015.
- [4] A. Tessmann, A. Leuther, H. Massler, M. Kuri and R. Loesch, "A Metamorphic 220-320 GHz HEMT Amplifier MMIC," 2008 IEEE Compound Semiconductor Integrated Circuits Symposium, Monterey, CA, USA, 2008, pp. 1-4.
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- [9] M. Urteaga, Z. Griffith, M. Seo, J. Hacker, M. Rodwell, “InP HBT Technologies for THz Integrated Circuits”, Proceedings of the IEEE, Vol. 105, No. 6, pp 1051-1067 June 2017.
- [10] H. A. Haus and R. B. Adler, "Optimum Noise Performance of Linear Amplifiers," in Proceedings of the IRE, vol. 46, no. 8, pp. 1517-1533, Aug. 1958.
- [11] A. Singhakowinta & A. R. Boothroyd, "Gain Capability of Two-port Amplifiers", International Journal of Electronics, Volume 21, Issue 6, 1966, pages 549-560.
- [12] H. Fukui, "Available Power Gain, Noise Figure, and Noise Measure of Two-Ports and Their Graphical Representations," in IEEE Transactions on Circuit Theory, vol. 13, no. 2, pp. 137-142, June 1966.
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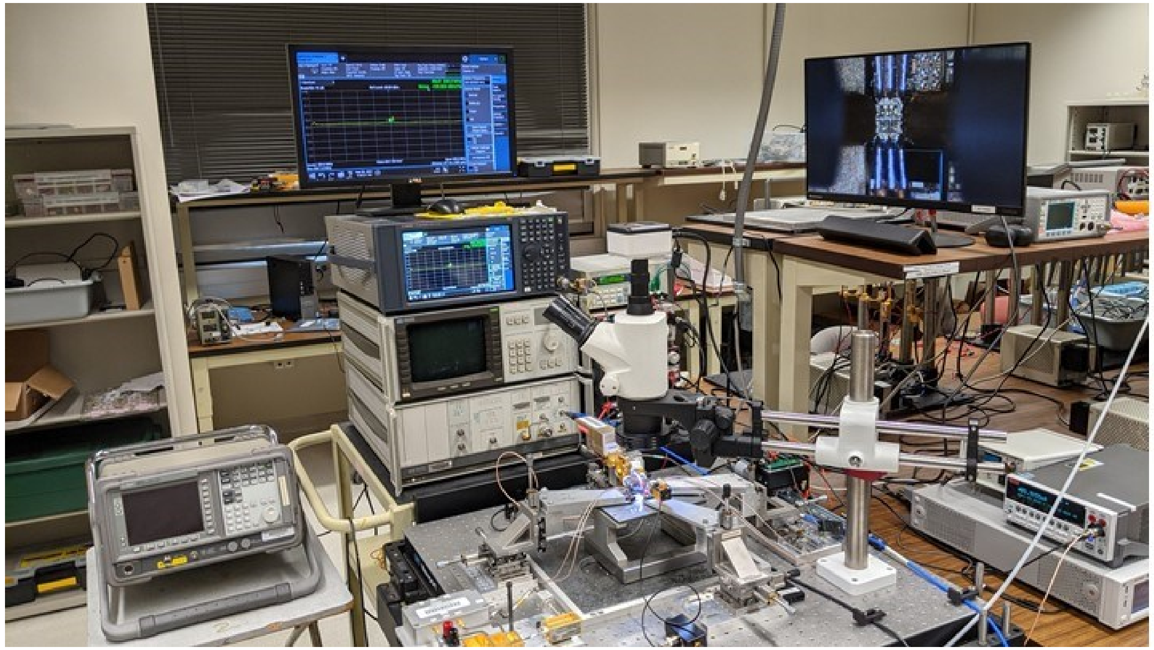
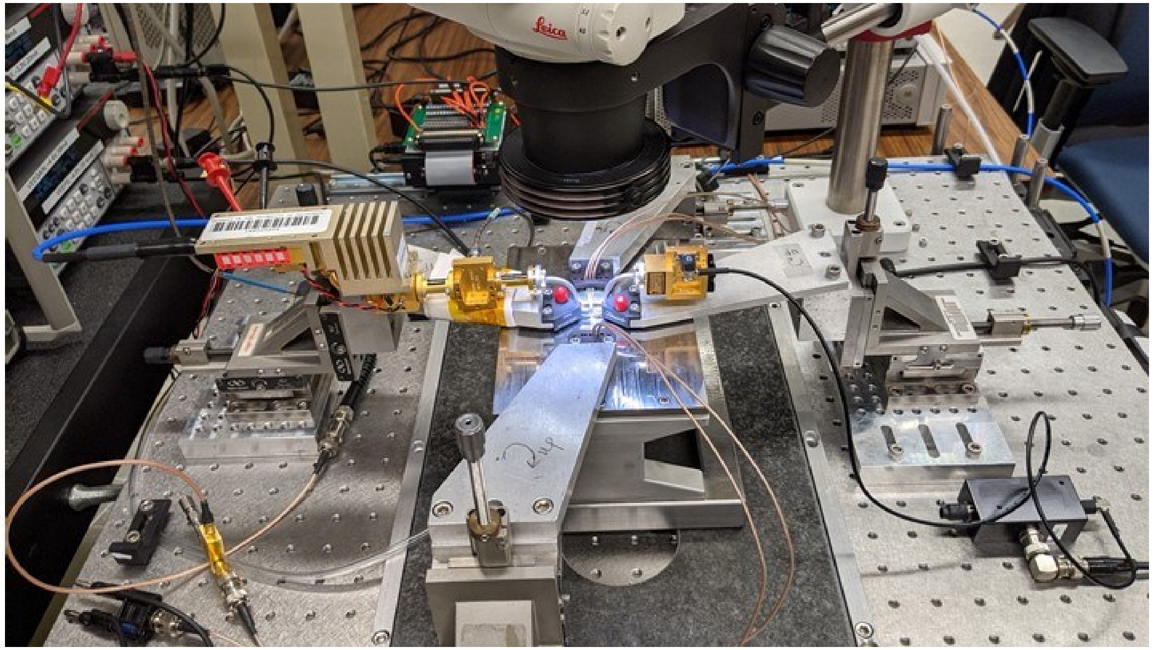
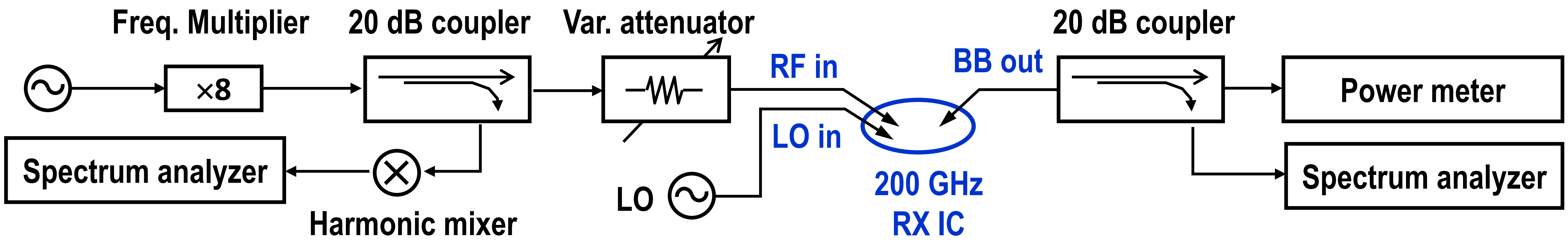
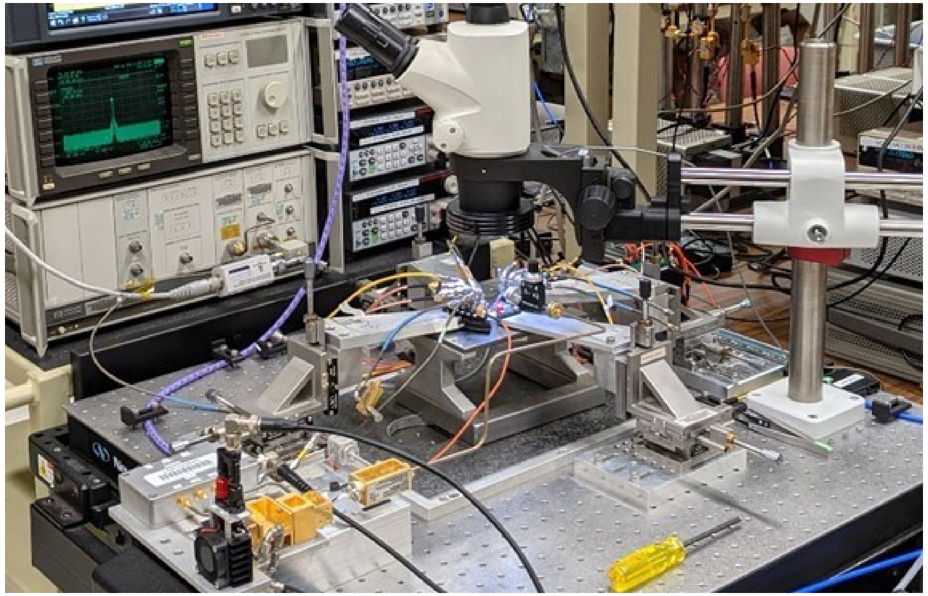
Setup: Noise Measurement (Pictures)





Receiver Testing Setup

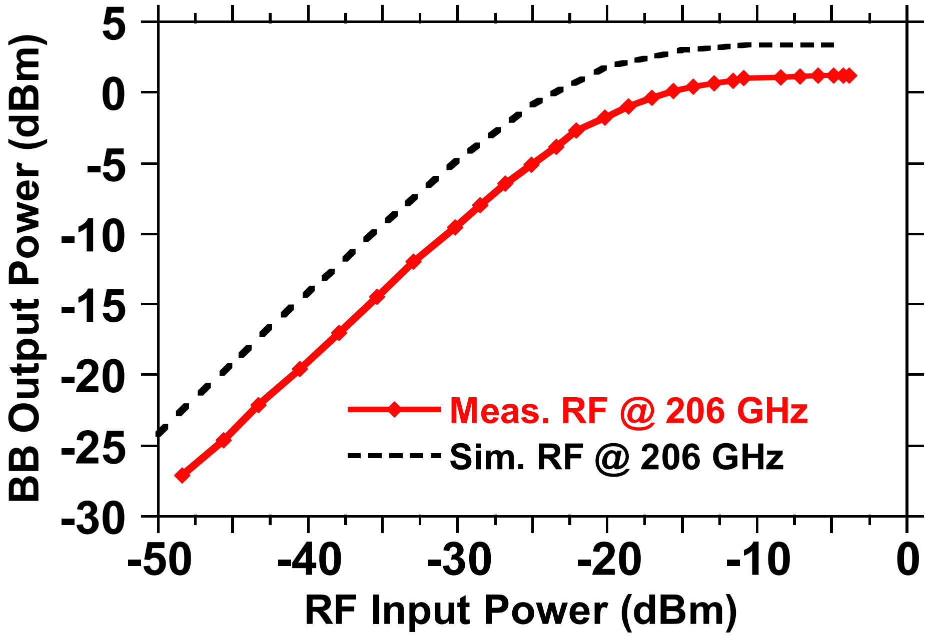




- 140-220 GHz (WR5) on-wafer testing
- Simultaneous freq. & power testing
- RX driven by multiplier & variable attenuator

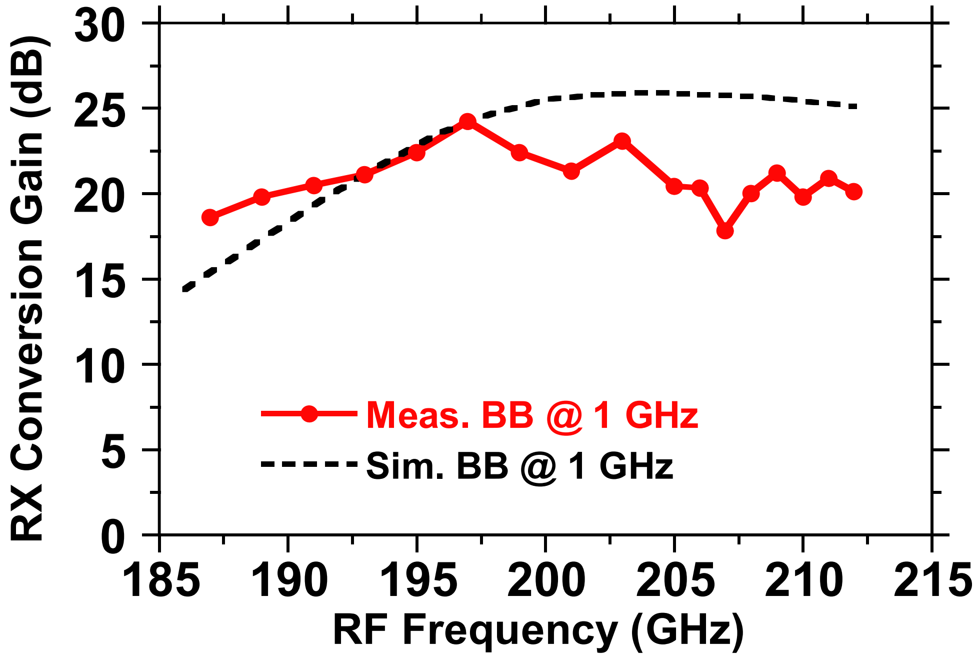
Measured Rx Power and Conversion Gain

P_{out} vs P_{in} @ f_{LO}=206 GHz (f_{BB}=1 GHz)



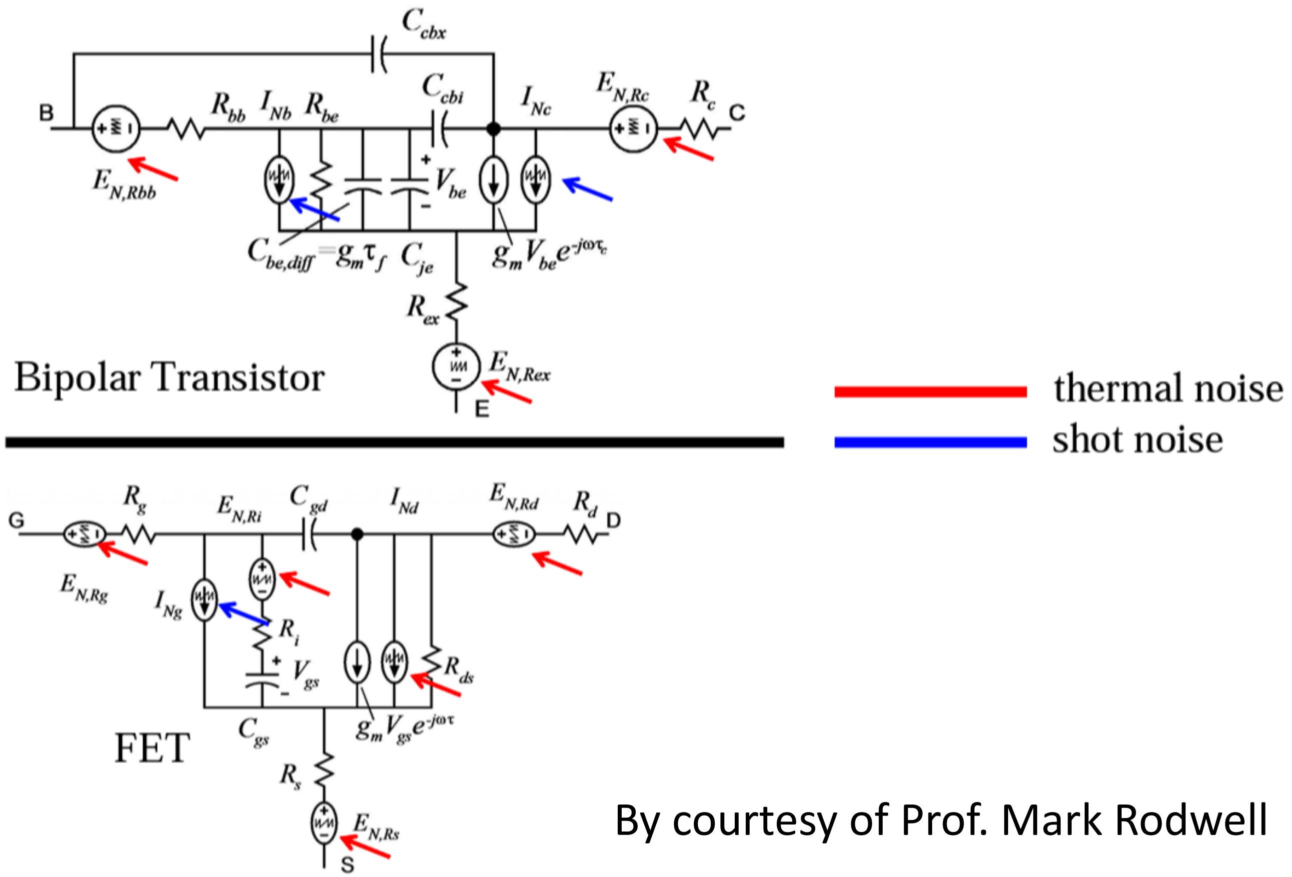
- Input P_{1dB} = -24 dBm
- P_{sat} = +1 dBm
- P_{DC} = 825 mW

Conversion Gain @ fixed f_{BB}



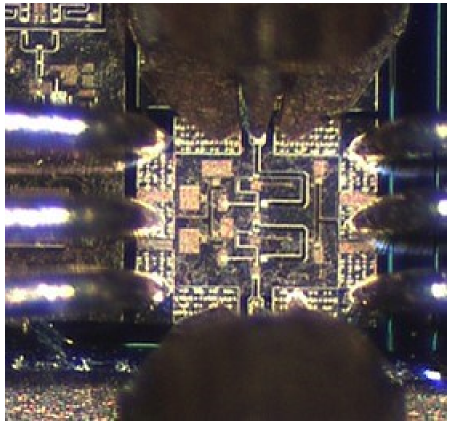
- Peak conversion gain = 22 dB
- LO multiplier tuning bandwidth > 25 GHz

Noise: HBT vs HEMT

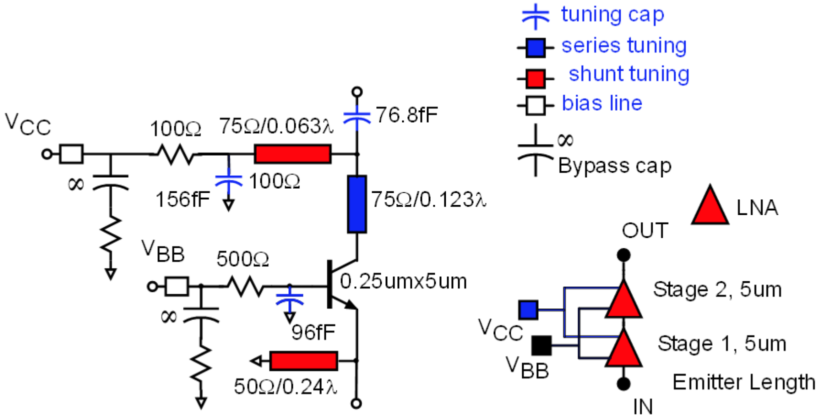


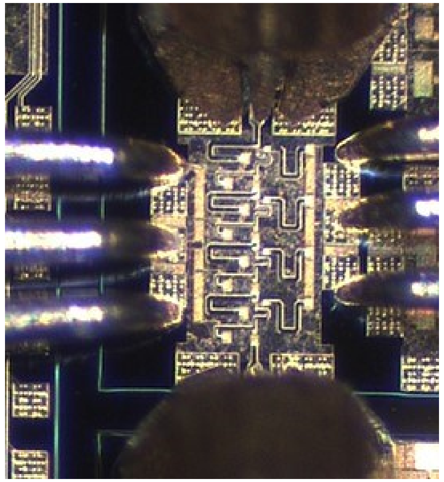
By courtesy of Prof. Mark Rodwell

CB and CE Low Noise Amplifiers



210GHz, Simulated	CB, 5um, 2 stage
Gain	13.6 dB
BW	33 GHz
NF	7.4 dB
$P_{1dB,in}$	-29.7 dBm
P_{DC}	9 mW
Die Area	290umx245um
$J_{emitter}$ V_{cb}	0.6mA/um 0.4V





200GHz, Simulated	CE, 5um, 4 stage
Gain	13.2 dB
BW	60 GHz
NF	8 dB
$P_{1dB,in}$	-16.8 dBm
P_{DC}	19.2 mW
Die Area	290umx465um
$J_{emitter}$ V_{cb}	1.0mA/um 0.56V