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***W04**: Submillimetre-wave Monolithic Integrated Circuits*

SiGe HBT Based S-MMICs

Sorin P. Voinigescu
University of Toronto

EuMIC 2012
The 7th European Microwave Integrated Circuits Conference

42ND EUROPEAN MICROWAVE CONFERENCE 2012
The 42nd European Microwave Conference

Credits

Graduate students

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- Andreea Balteanu
- Alex Tomkins
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- Katya Laskin

Collaborators

- Dr. Juergen Hasch
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- Prof. Thomas Zwick
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- Stefan Beer

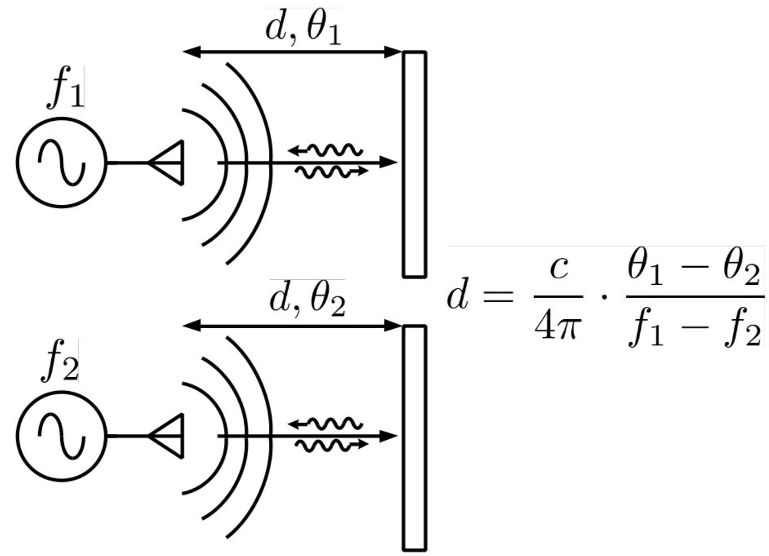
- NSERC, Robert Bosch GmbH for funding
- STMicroelectronics for chip donations
- Bernard Sautreuil and Patrick Cogez for technology access
- Jaro Pristupa and CMC for CAD and support

Outline

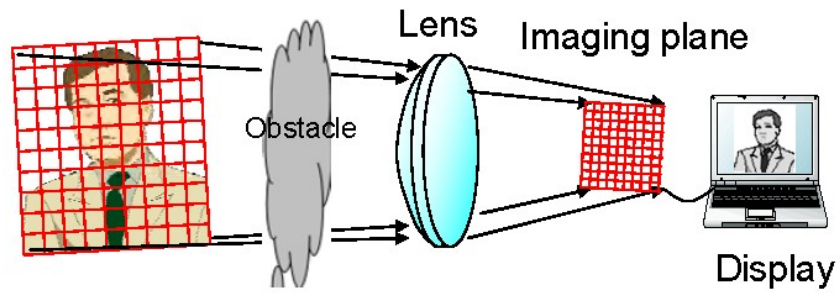
- Motivation
- Technologies
- 120-123 GHz Distance Sensor with above IC Antenna
- 150-170 GHz Transceiver with 3 on Die Antennas
- 143-150 GHz SUCCESS Sensor with BIST
- Potential Solutions for G-Band Sensors

Applications

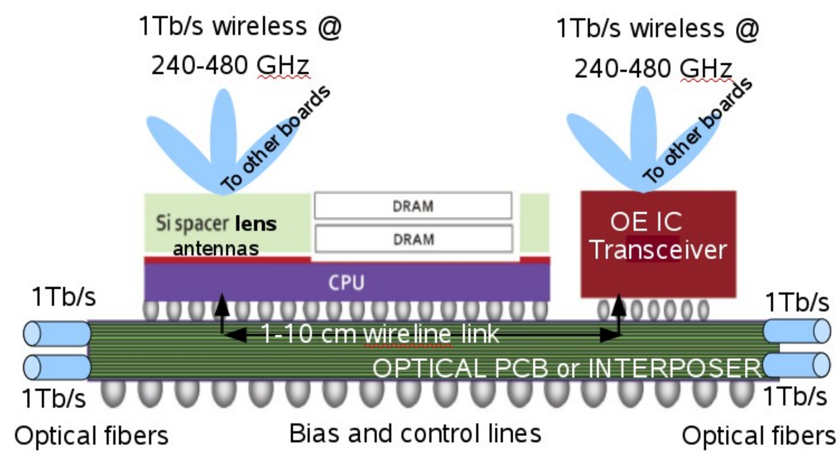
- Industrial range and Doppler sensors



- Active/passive imagers for security and remote sensing



- 100+Gb/s short-range reconfigurable wireless data transmission in the data center



Wish list for submillimeter radio/radar

- P_{TX} = 10 dBm
- PN < -90 dBc/Hz in band, <-140 dBc/Hz beyond 50 MHz
- NF < 12 dB
- P_{DC} < 1W
- BW > 20% (for passive imaging and 100+Gbs radio)
- QPSK, 16/64 QAM modulation schemes
- 50-100 Gb/s digital streams in TX
- 100 GS/s 8-10 bit ADC in receiver

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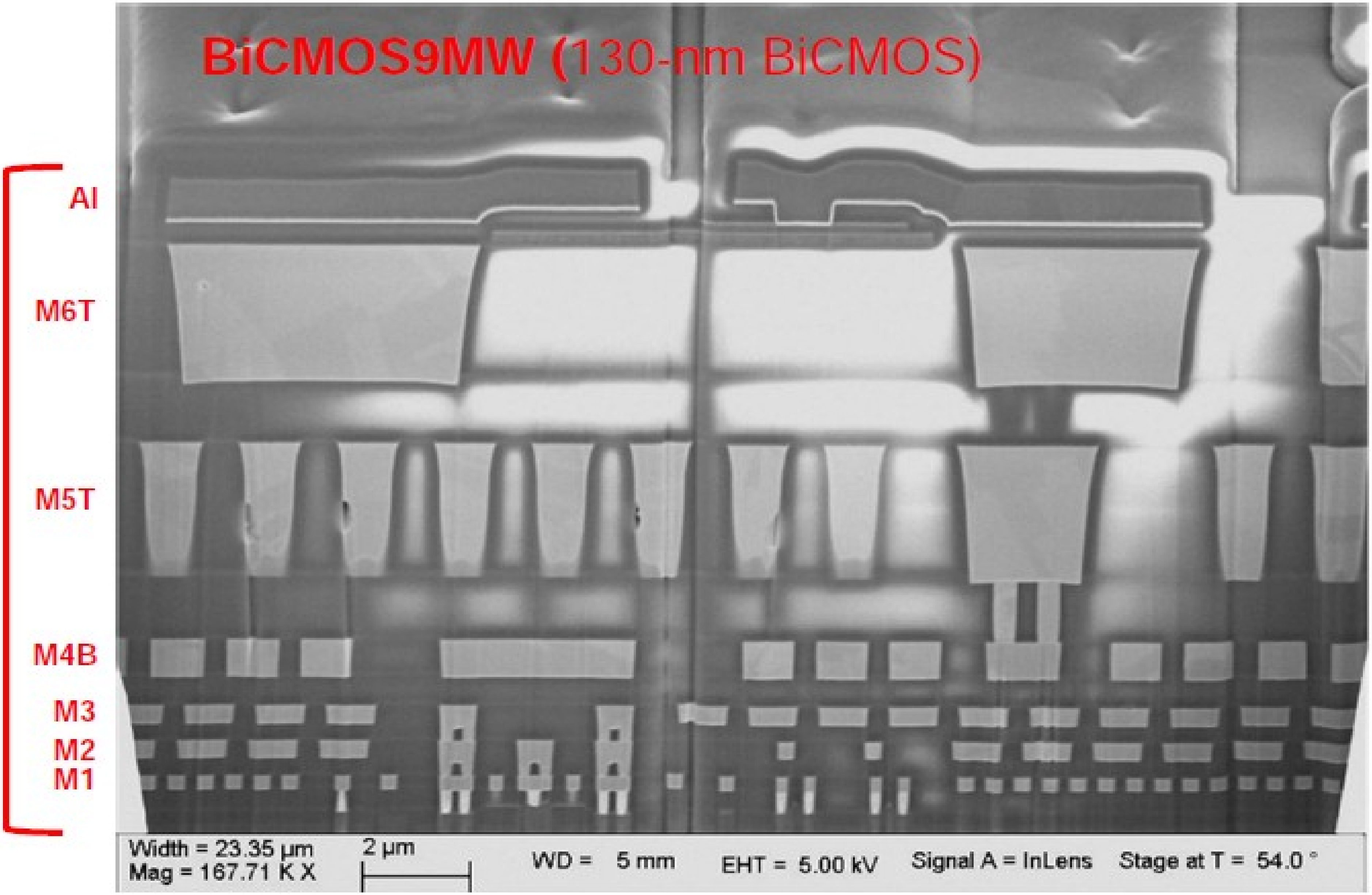
STMicroelectronics' 130-nm SiGe BiCMOS

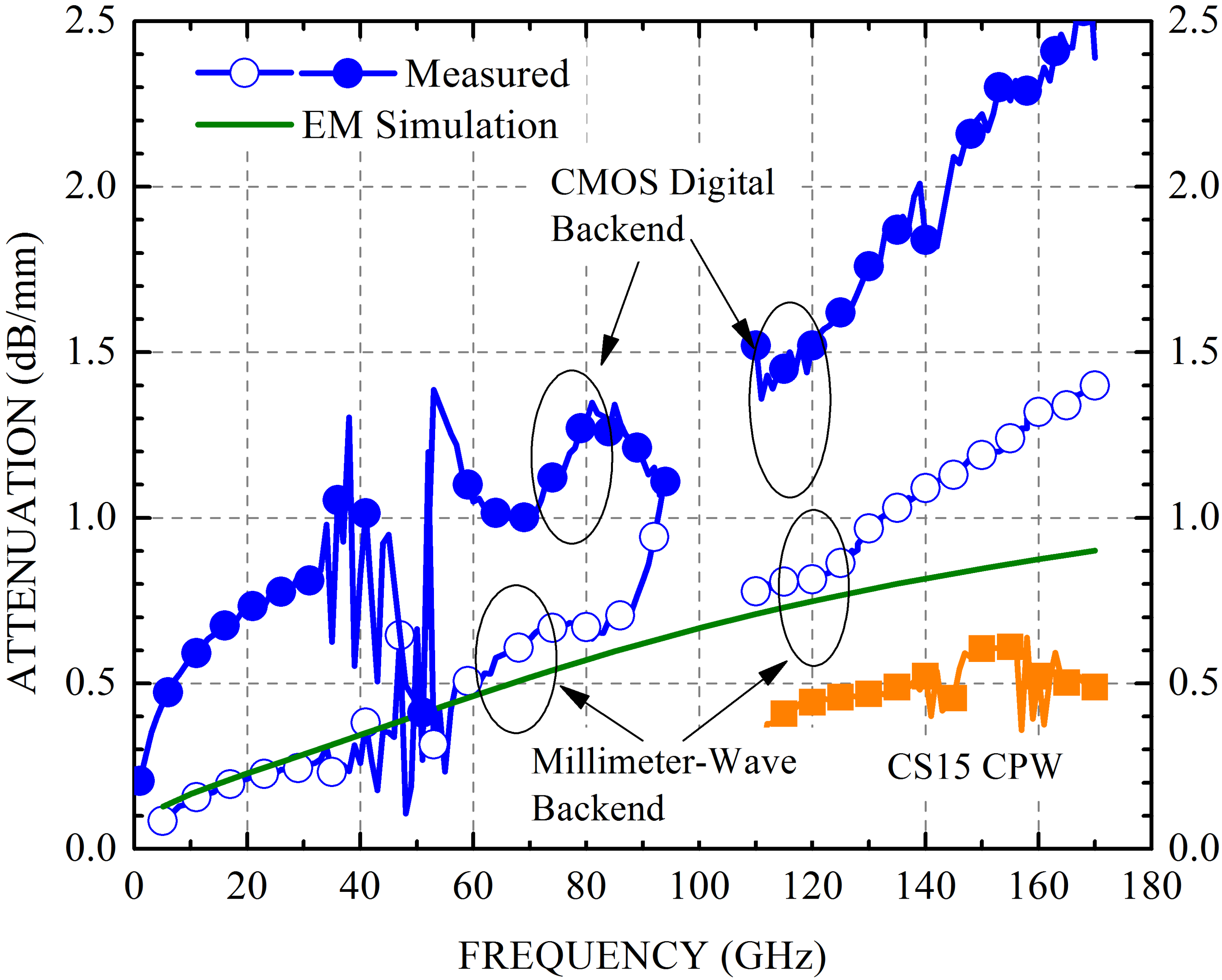
6ML BEOL ⇨ α = 0.7 dB/mm at 100 GHz

(Al+M6 with M1+M2 shield for Z_C = 50 Ω)



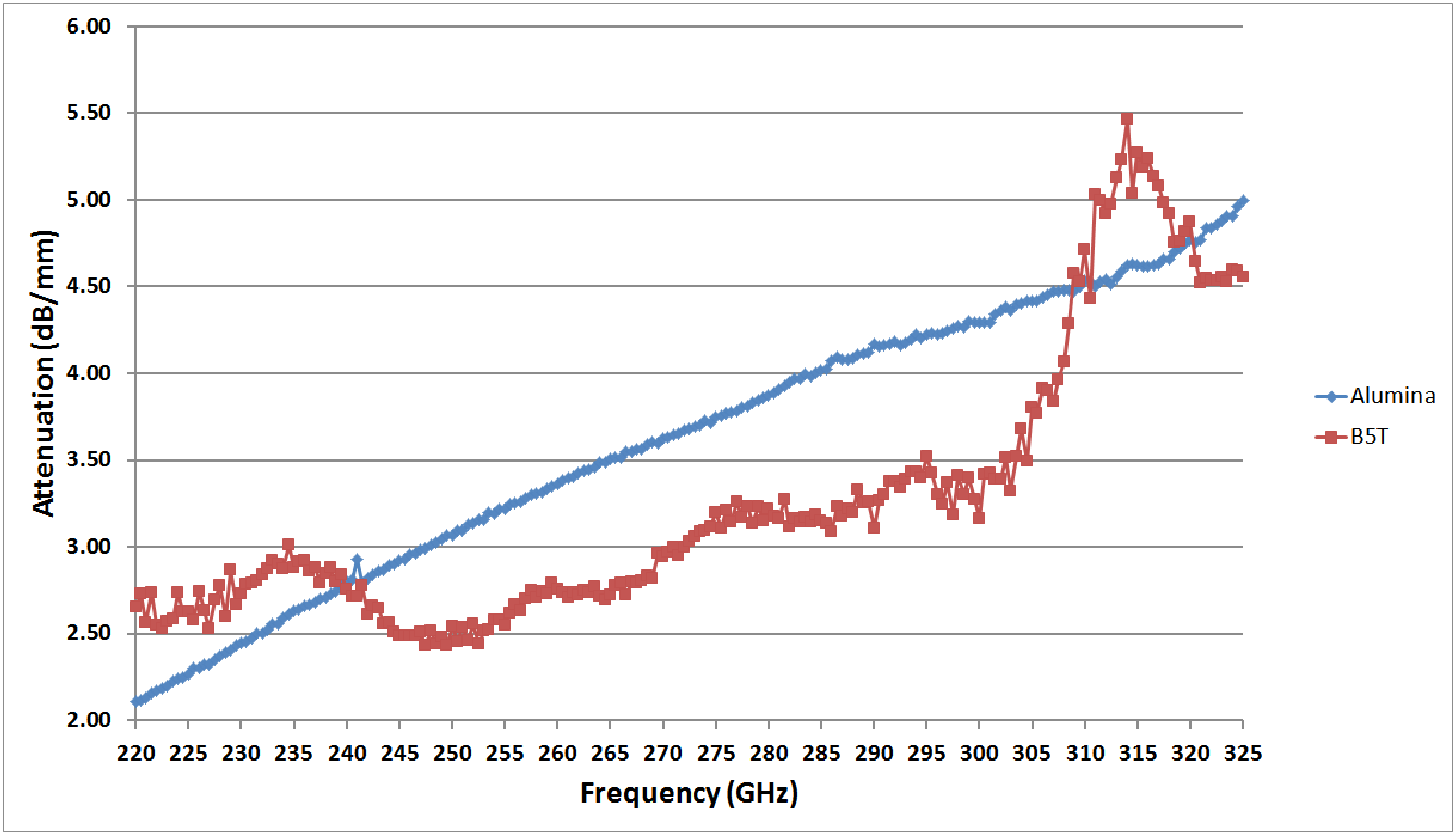
[Pascal Chevalier, CSICS-2012]

CMOS, SiGe, ISS μ–strip lines: D-Band

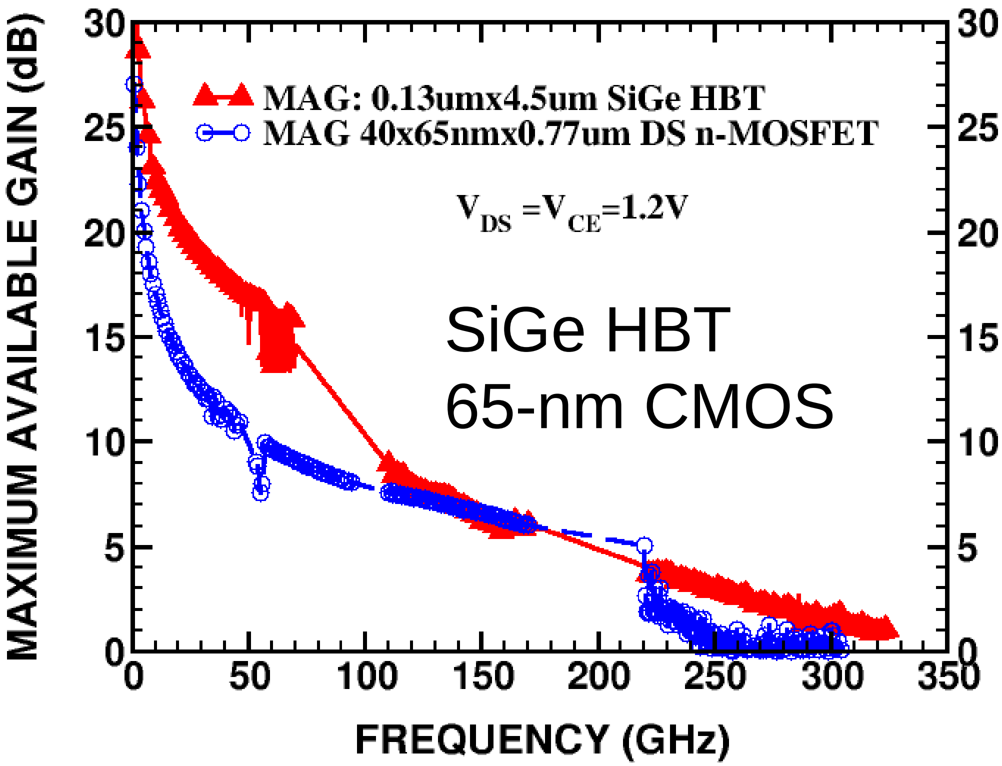


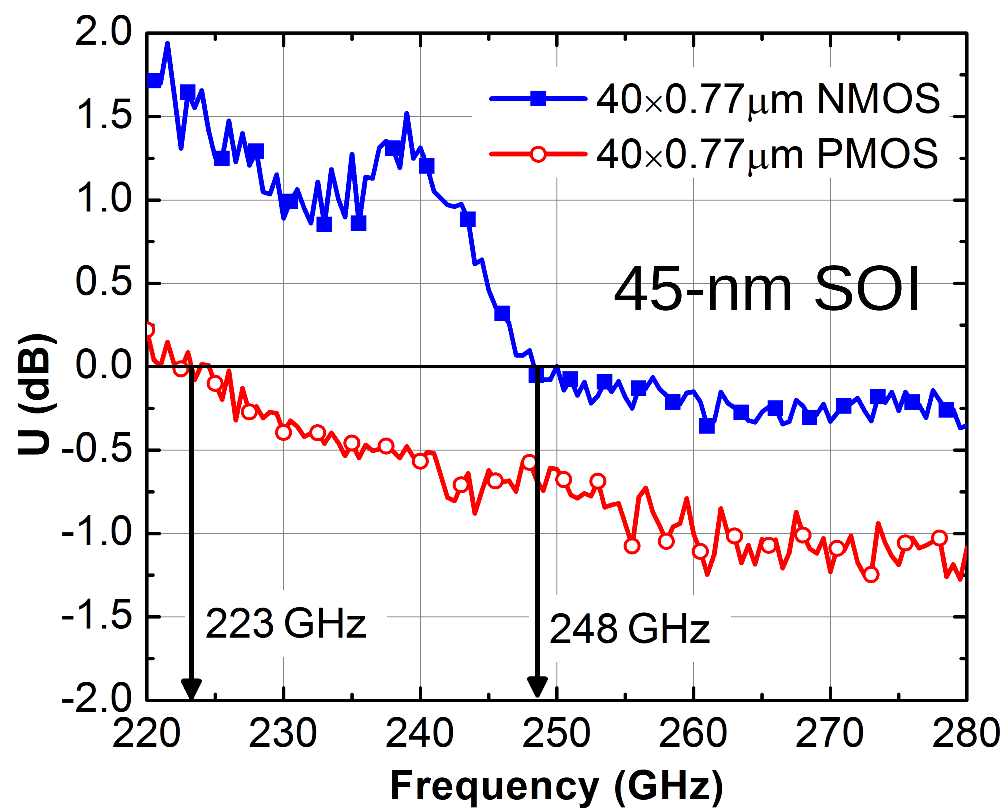
[Ken Yau, IEEE Micro Mag., Feb.-2012]

SiGe vs. ISS μ–strip lines: H-Band

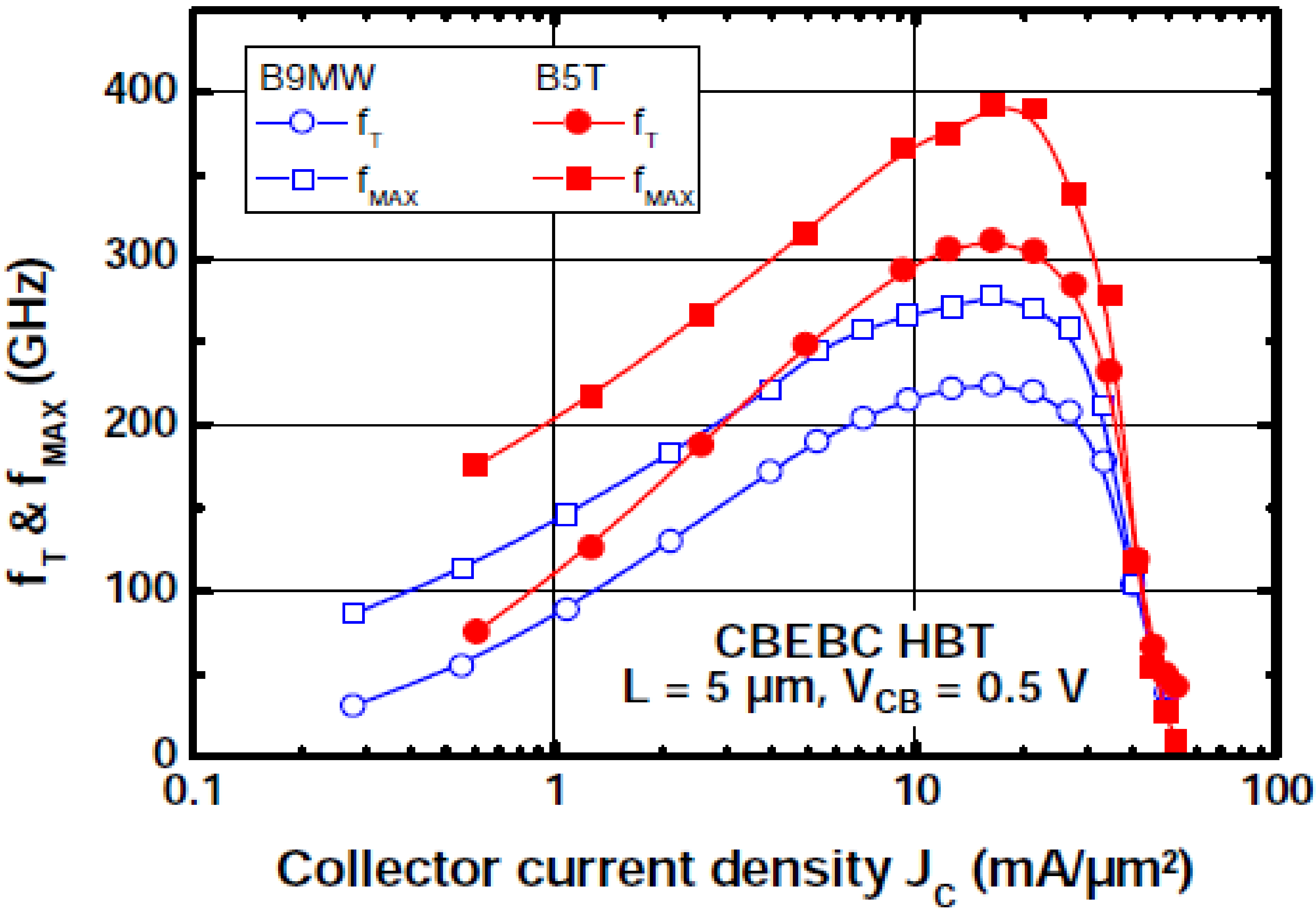


Si Transistor Performance at G-Band





SiGe HBT: BC9MW vs. B5T



[Pascal Chevalier, CSICS-2012]

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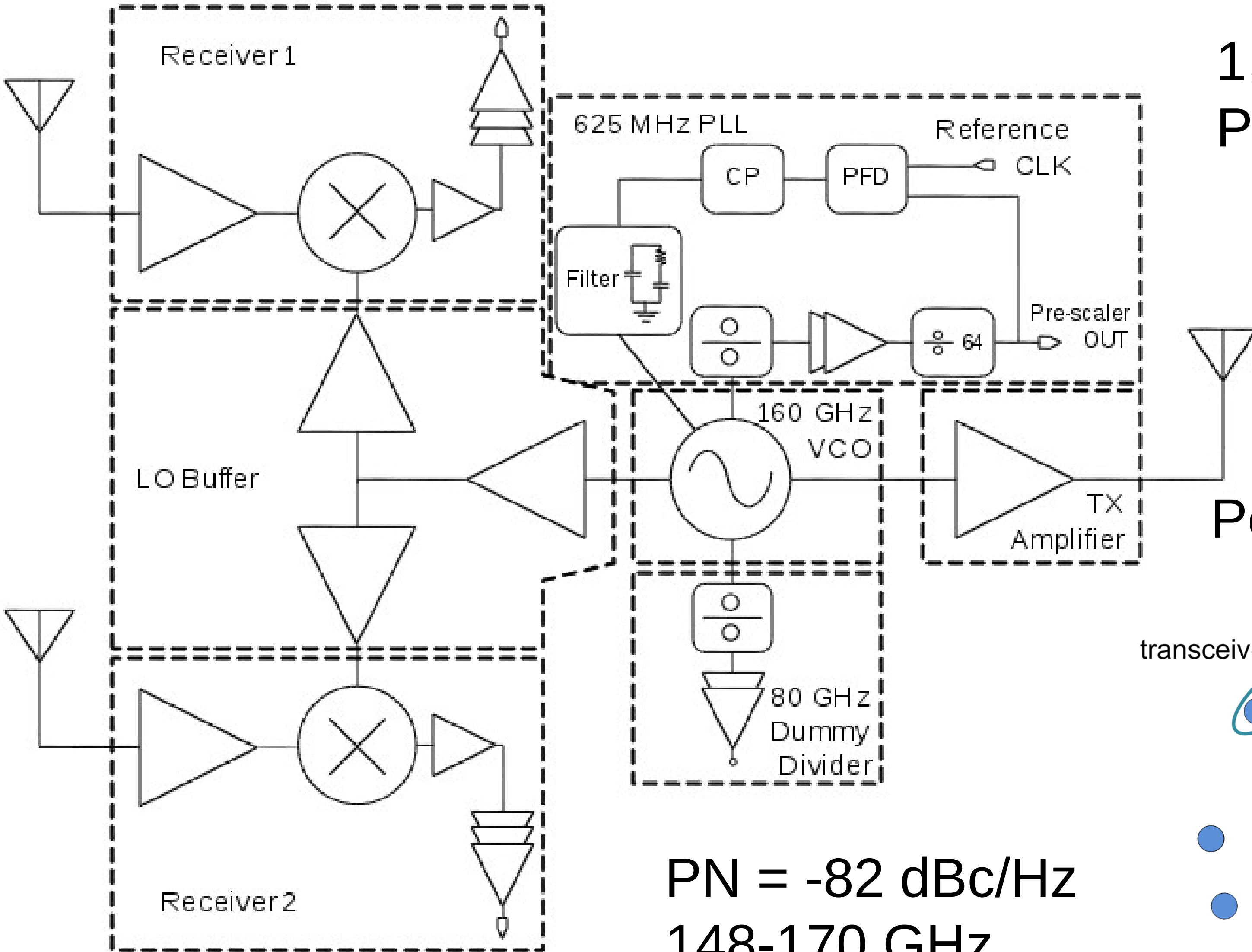
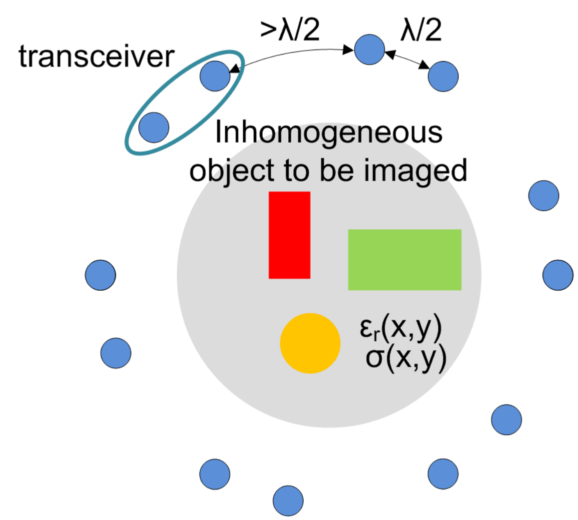
Dual Receive Channel Transceiver



1.5/2.5/3/3.6V

P_D = 1.8 W

Pout = 1 dBm



PN = -82 dBc/Hz

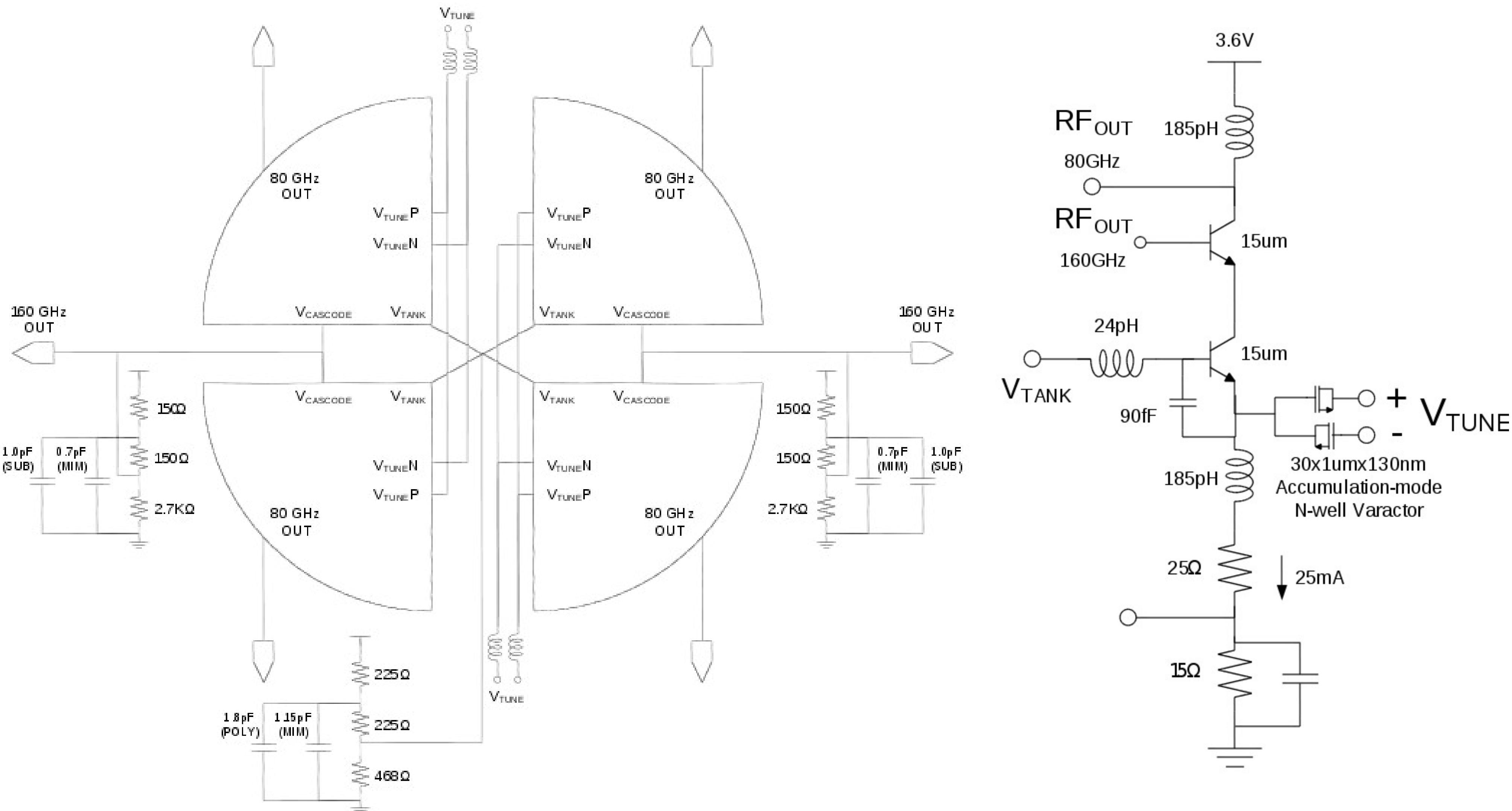
148-170 GHz

RX Gain = 27 dB

NF = 12 dB

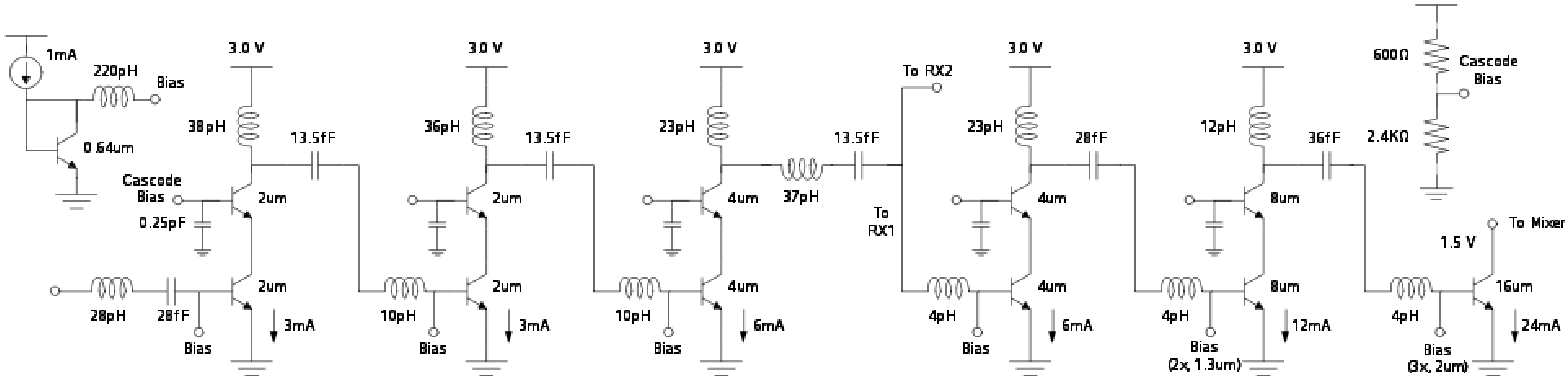
[I. Sarkas et al., MIKON-2012]

Push-Push 148-170 GHz VCO

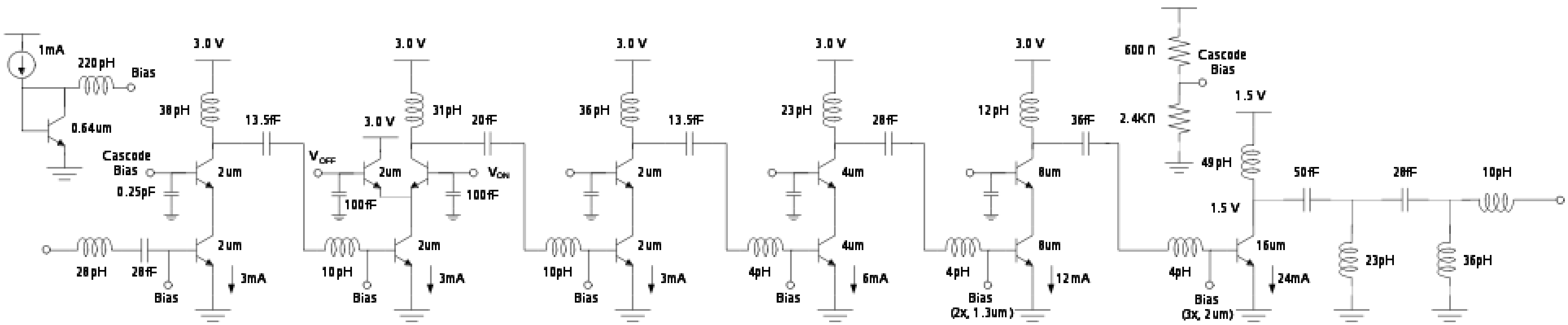


P_{DC} = 360 mW, P_{OUT} = -10 dBm, PN = -82 dBc/Hz at 1 MHz offset

148-170 GHz LO Tree and TX Amplifiers



P_D = 126 mW

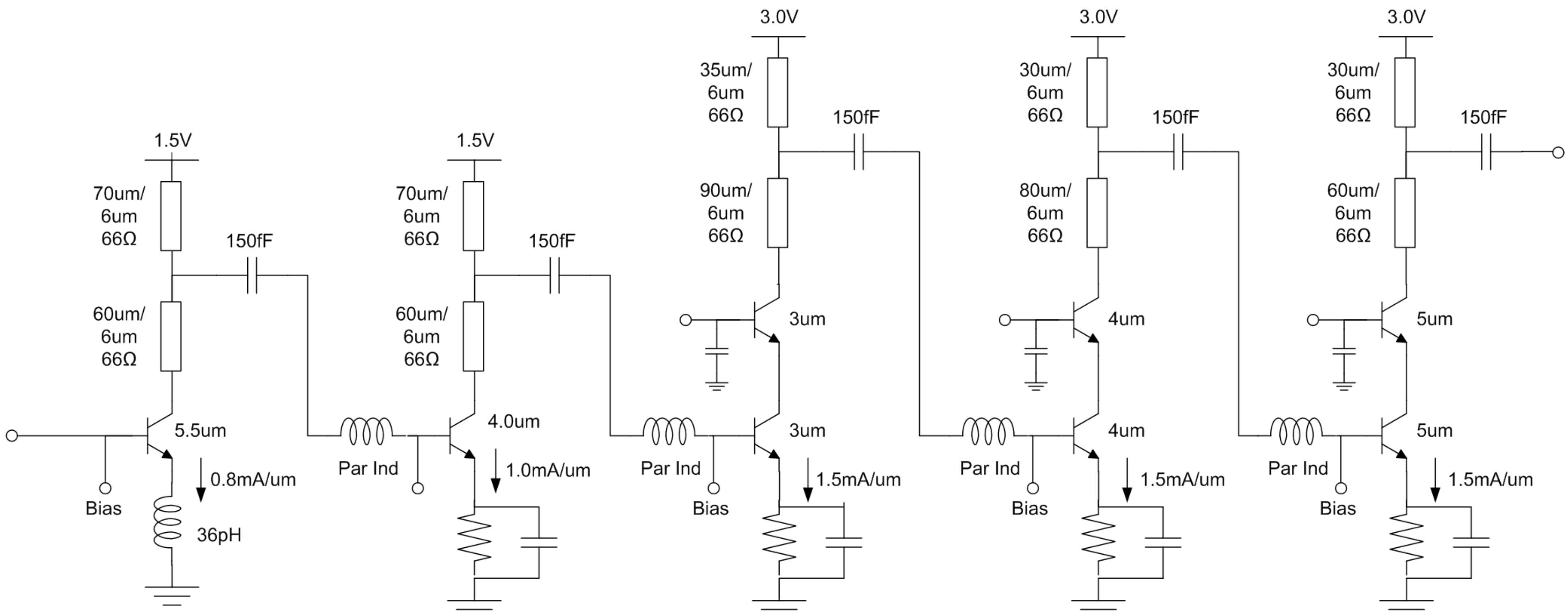


Amplitude Modulator

P_{out} > 2 dBm

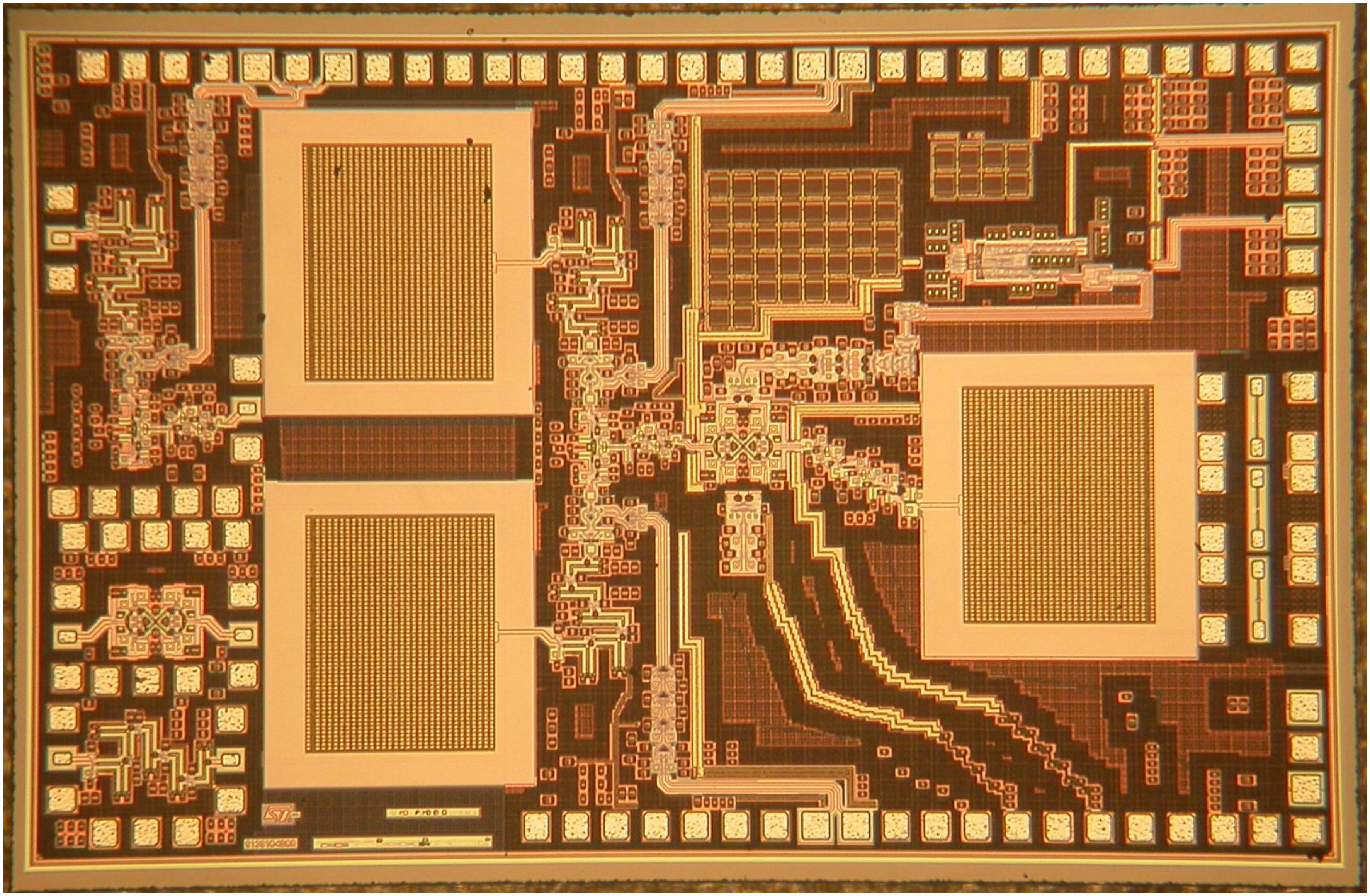
P_D = 117 mW

148-170 GHz Low Noise Amplifier



P_D = 67 mW, Gain= 20 dB, NF < 12 dB.

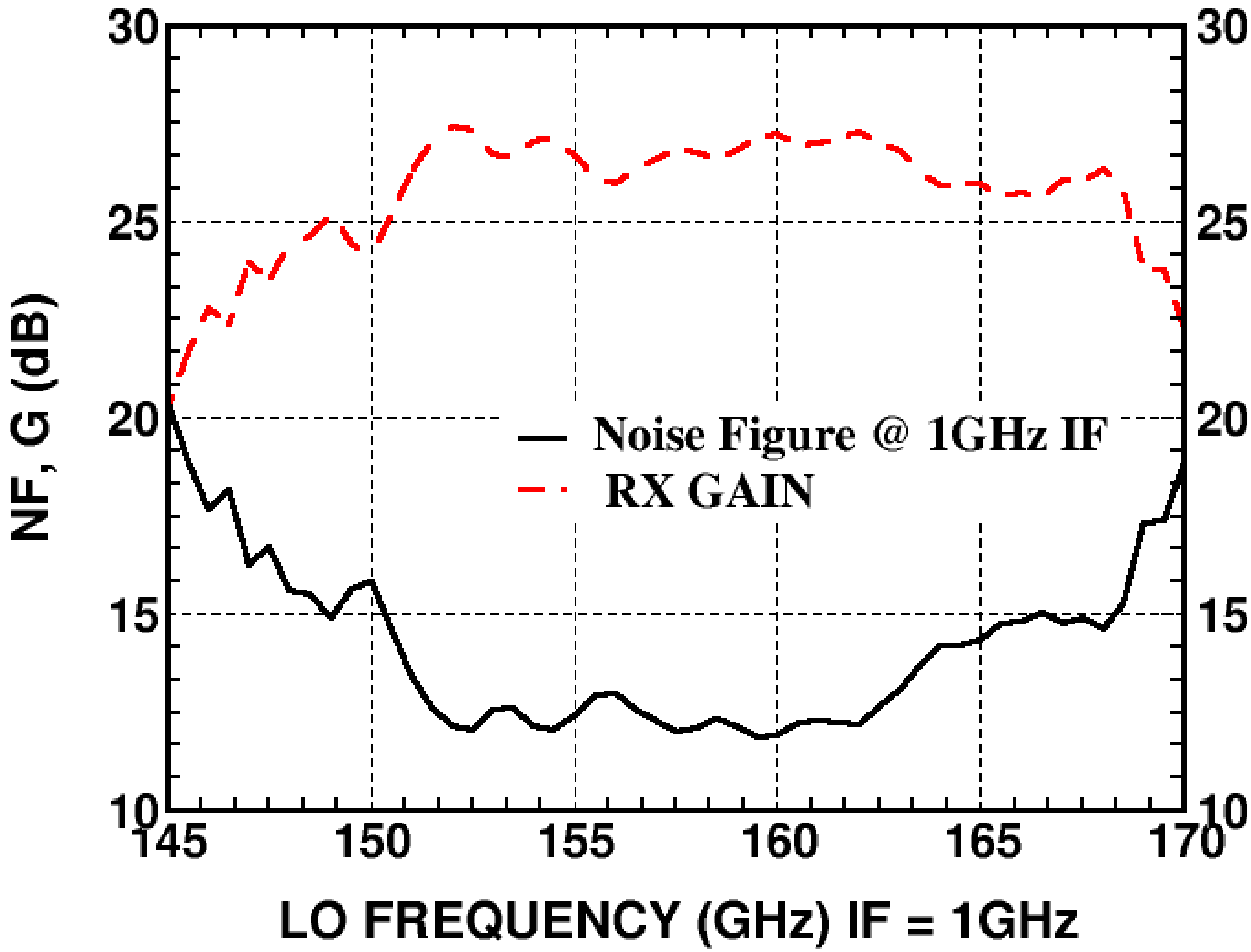
Die photograph



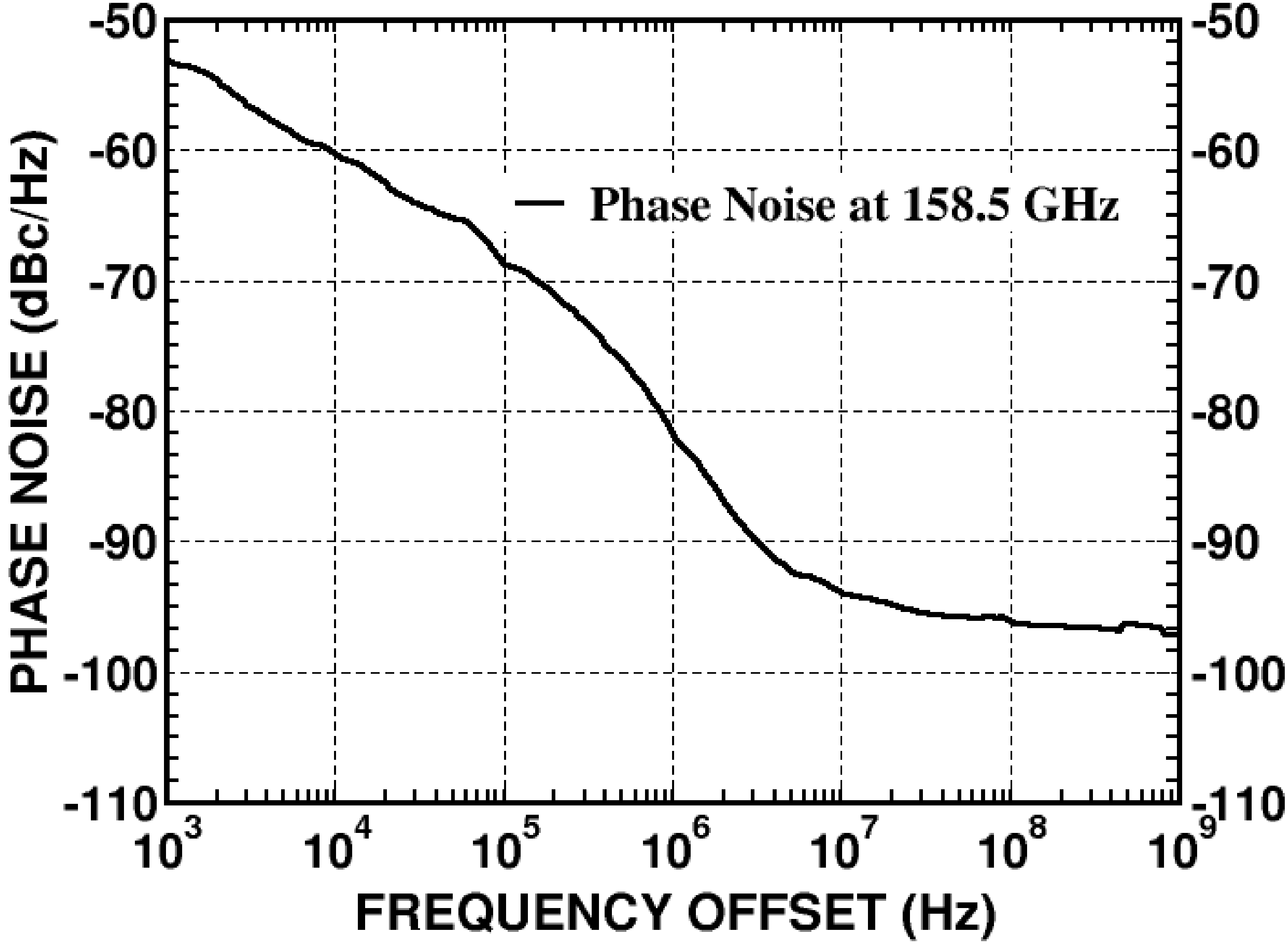
Chip: 2.1mm×2.9mm

130-nm BiCMOS9MW: SiGe HBT f_T= 230 GHz, f_{MAX} = 280 GHz

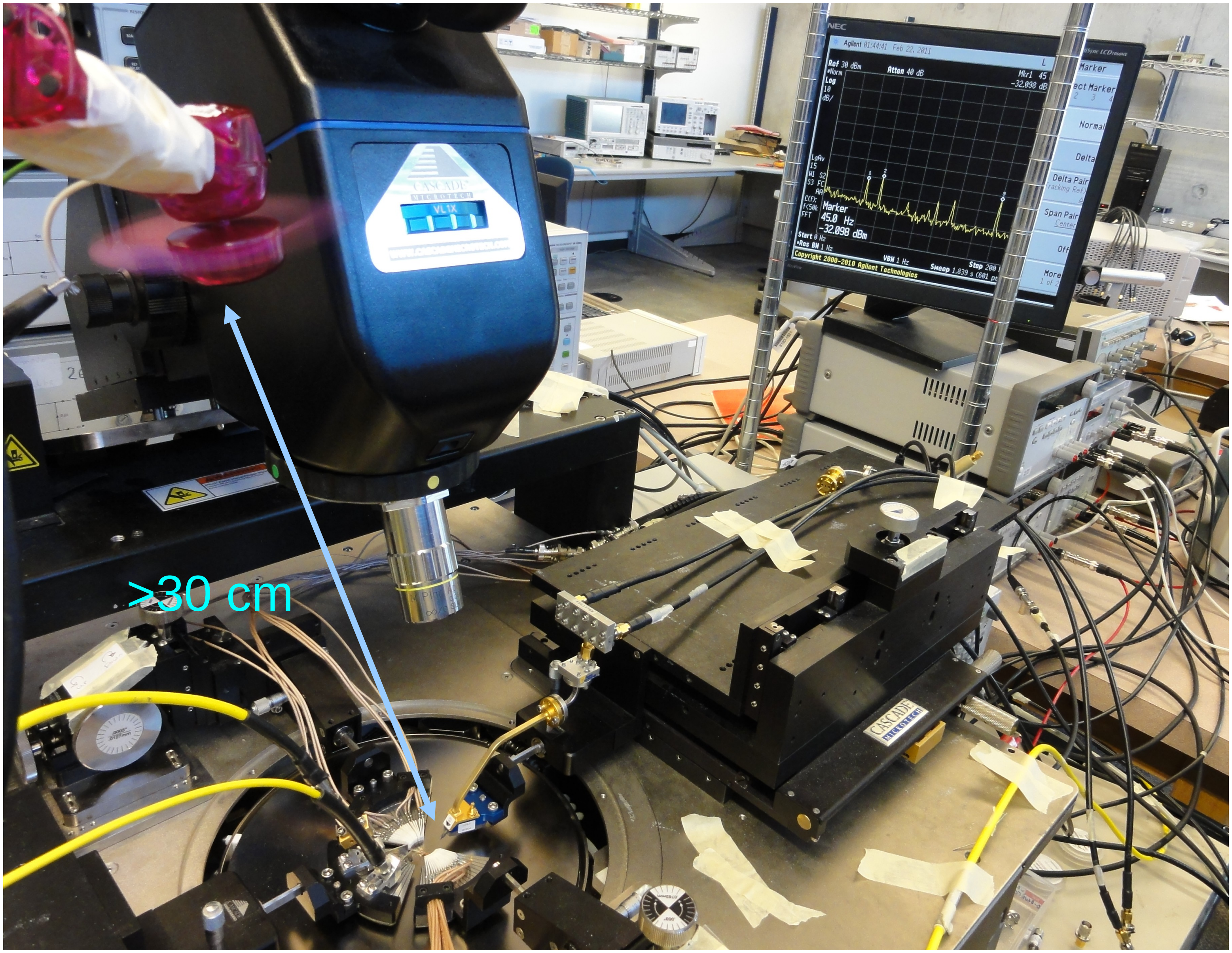
RX Breakout Gain and Noise Figure



Transceiver PLL Phase Noise



On-die Doppler Test



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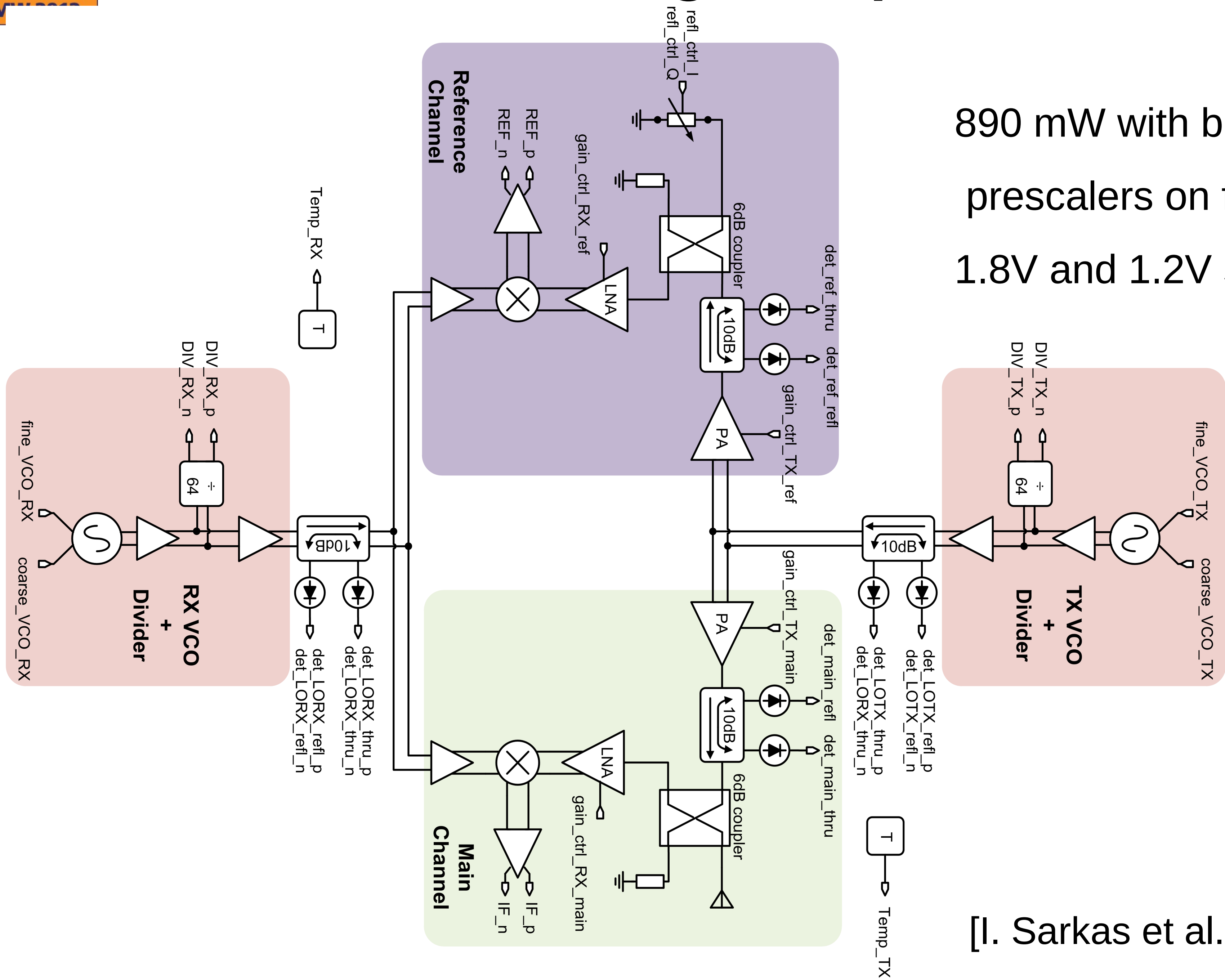
Monostatic single-chip sensor



890 mW with both

prescalers on from

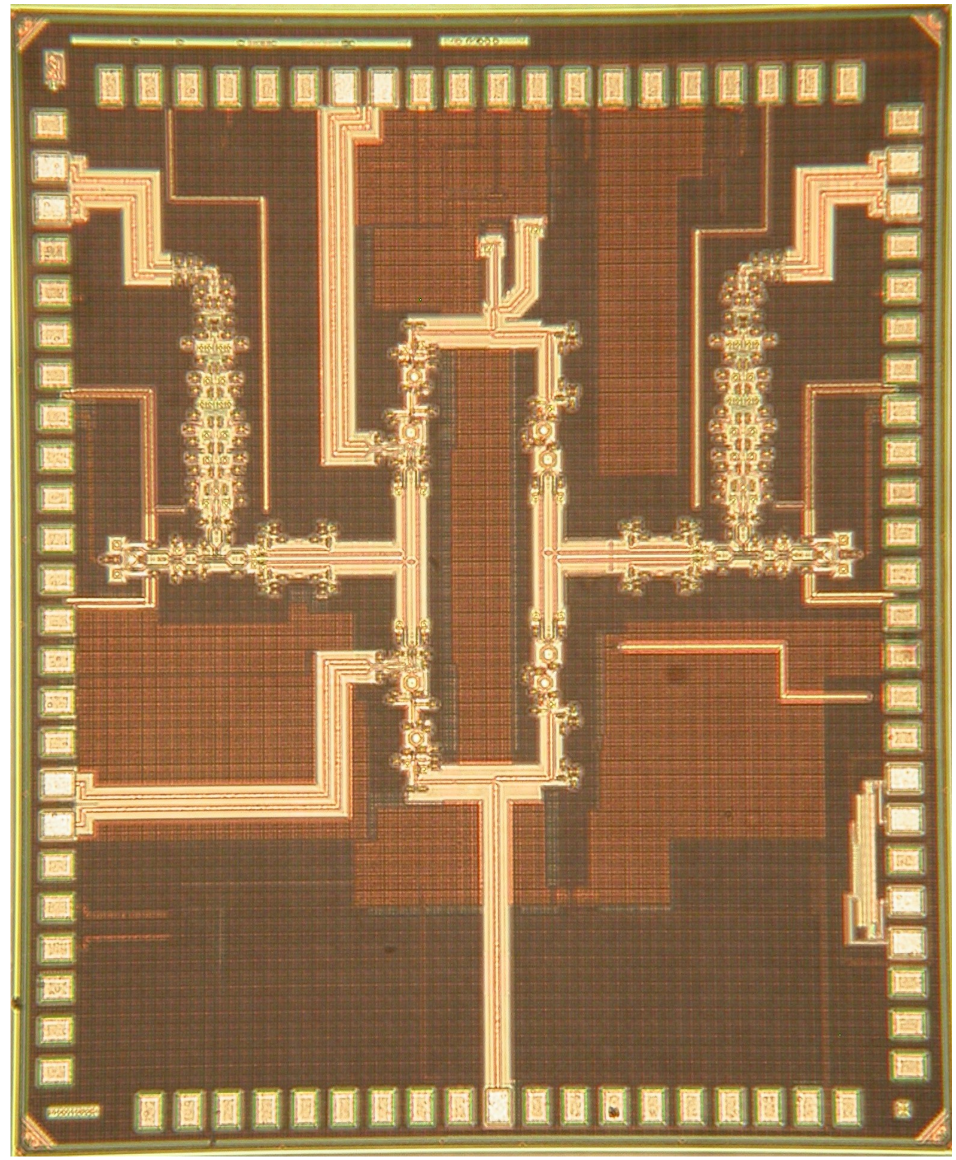
1.8V and 1.2V supplies

[I. Sarkas et al.CSICS 2012]

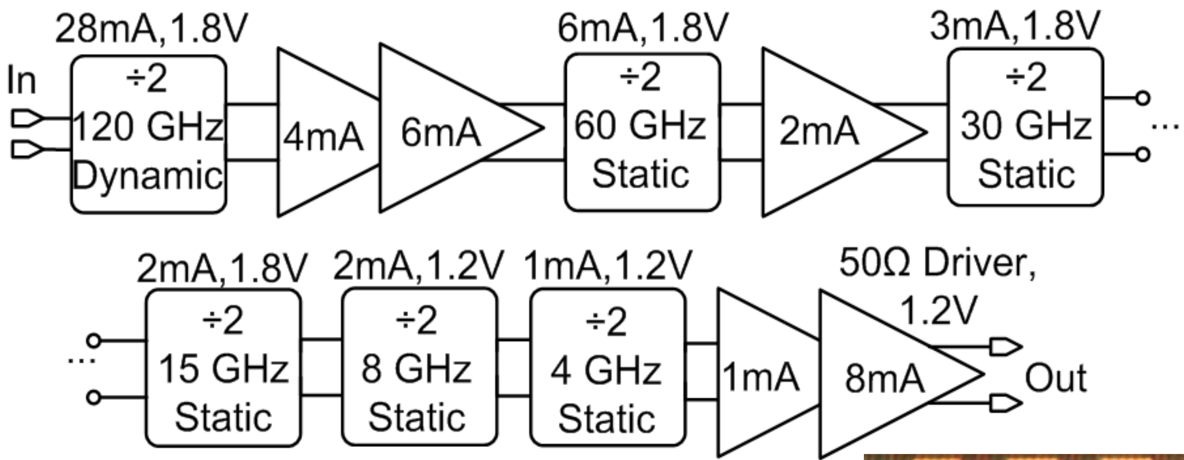
Layout and performance summary

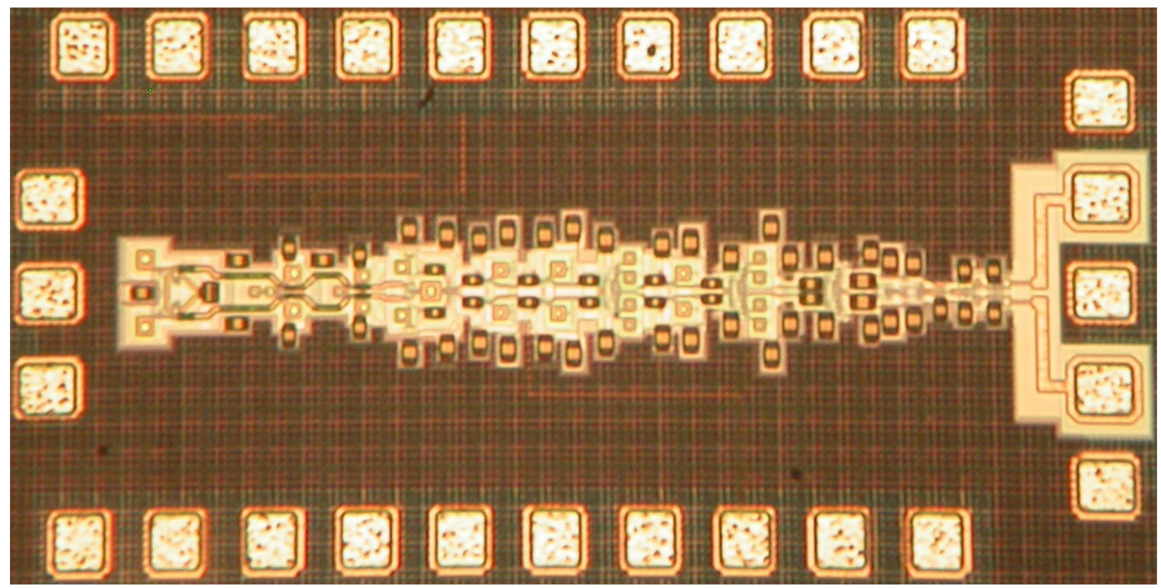
- BiCMOS9MW, f_T/f_{MAX}= 230/280 GHz
- Tuning range 143-152 GHz
- NF<10 dB, Pout >-6 dBm
- PN < -83 dBc/Hz at 1MHz
- P_{DC} = 800 mW
- Highest fundamental frequency transceiver

2.6mmx2.3mm



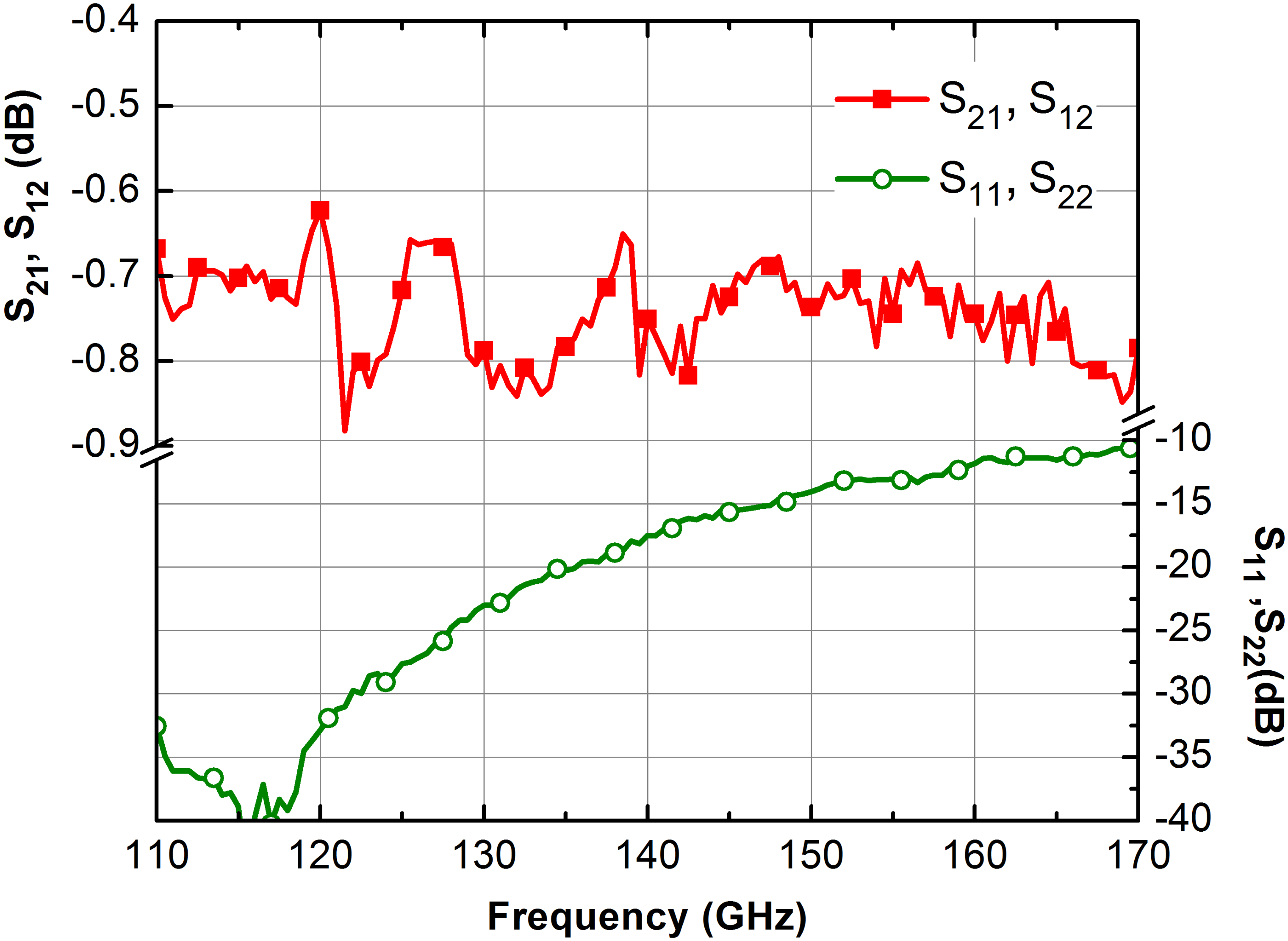
150-GHz Dynamic Divide-by-64

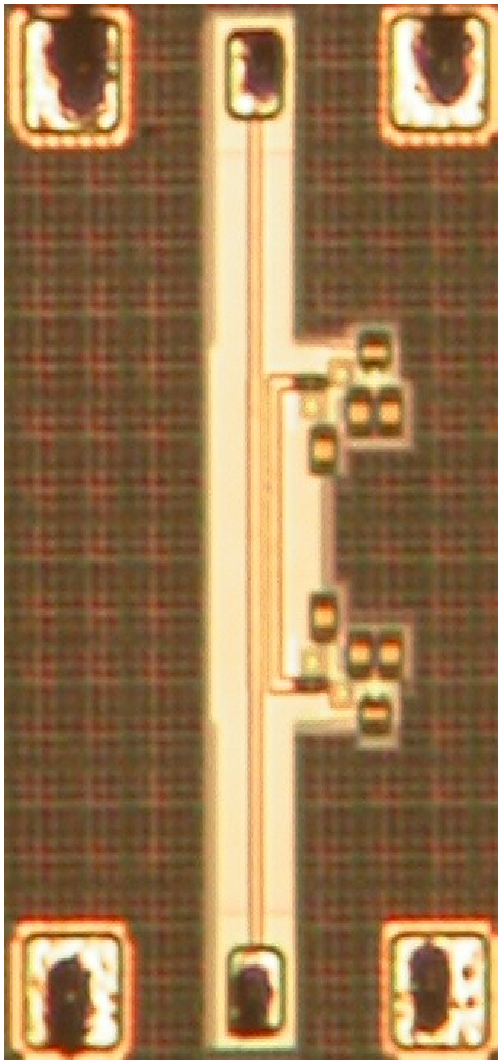




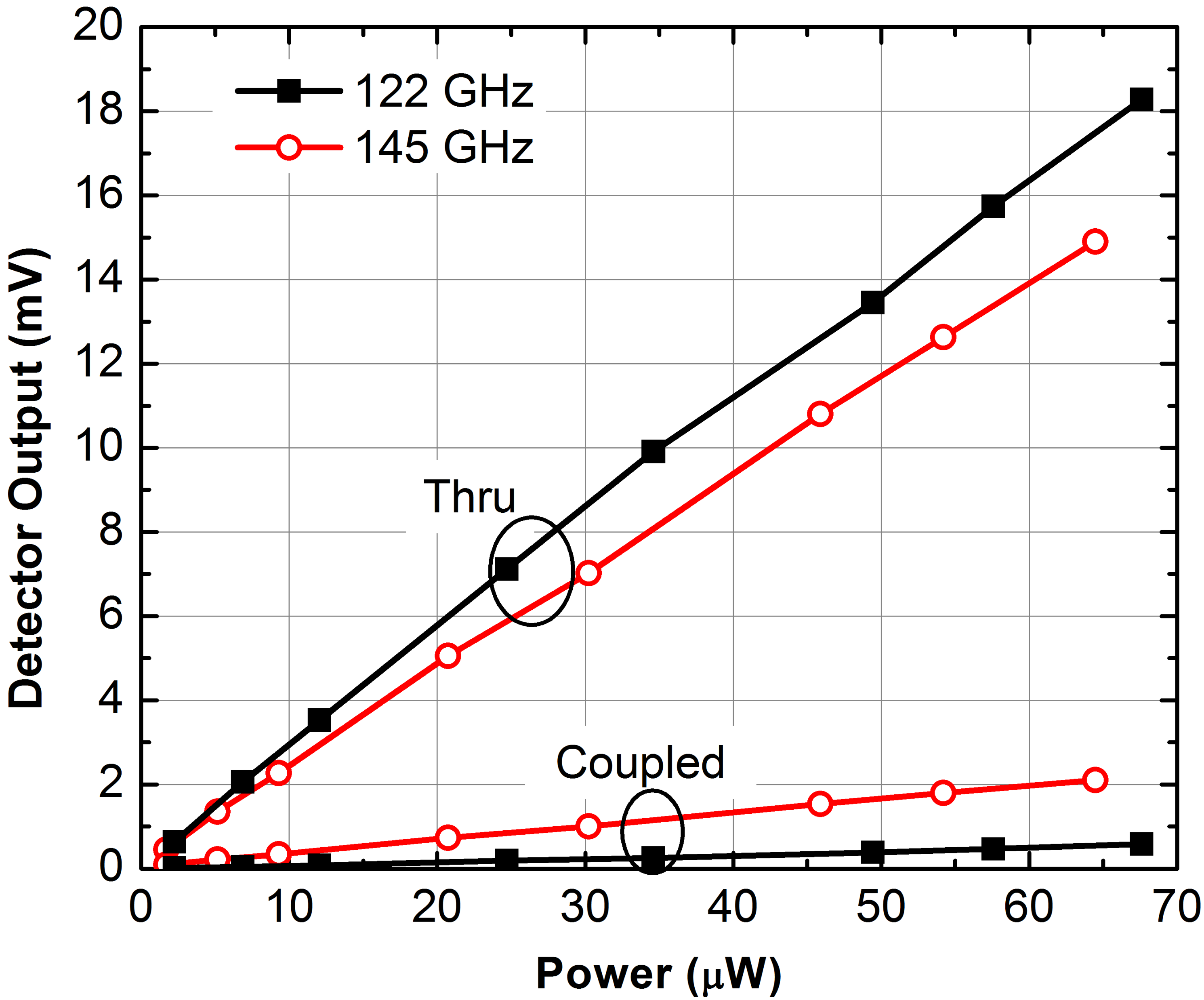
- Measured in test structure with 150-GHz VCO
- 1.8V/52mA + 1.2V/3mA= 97.2 mW + 25.2 mW in 50Ω buffer

Coupler with detectors

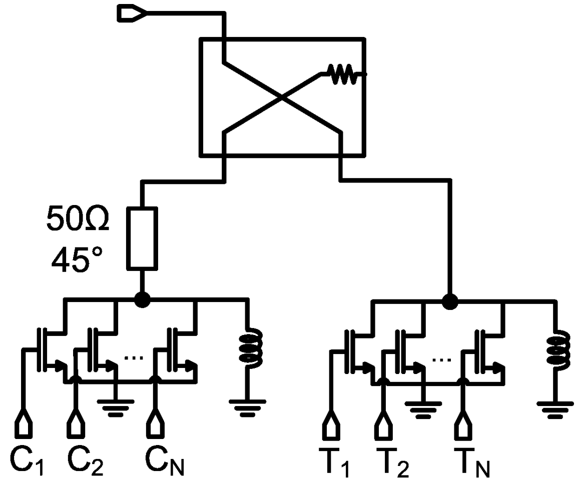


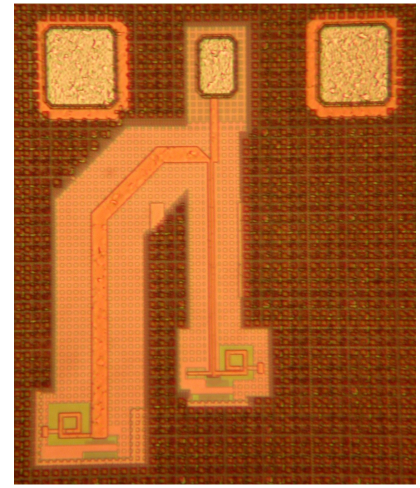


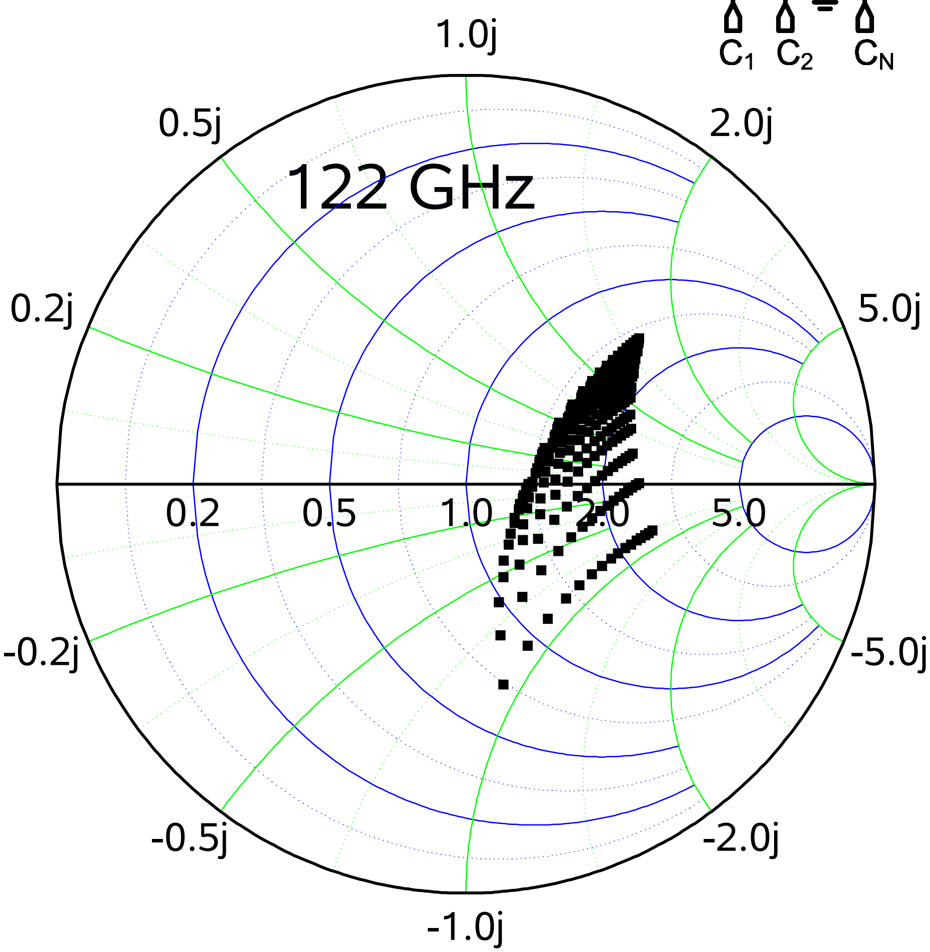
Coupler with detectors: Linearity

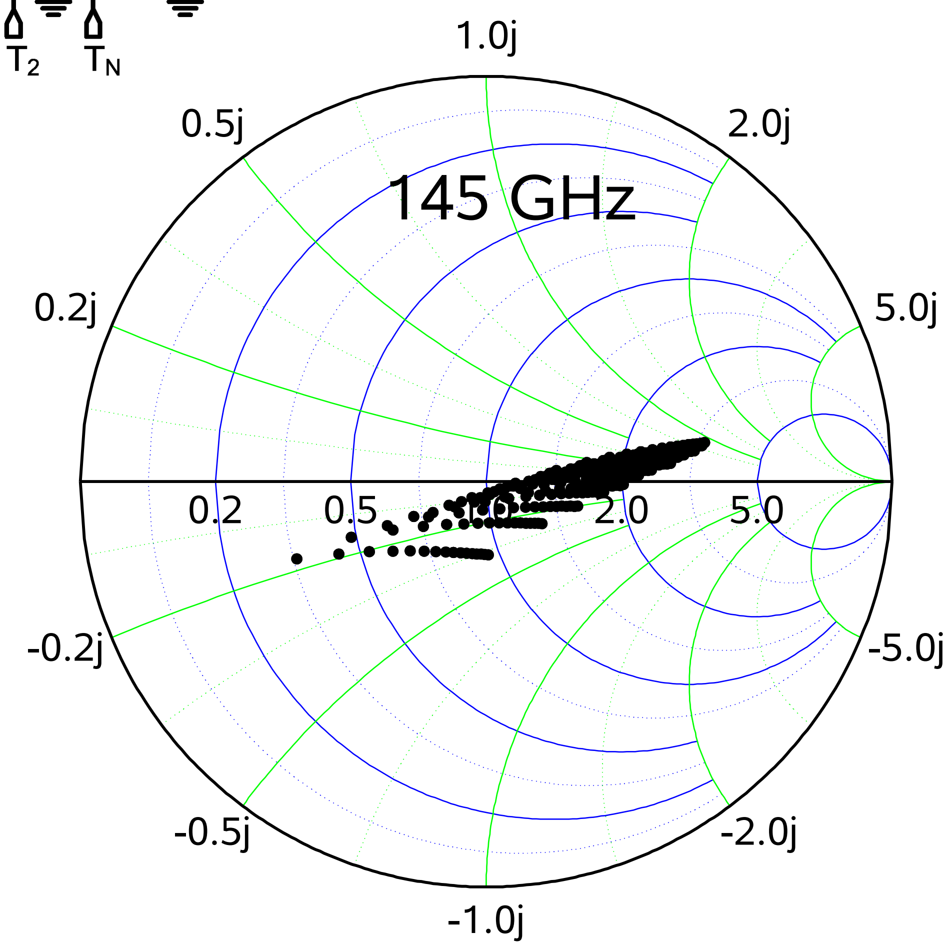


Digital Tuner States

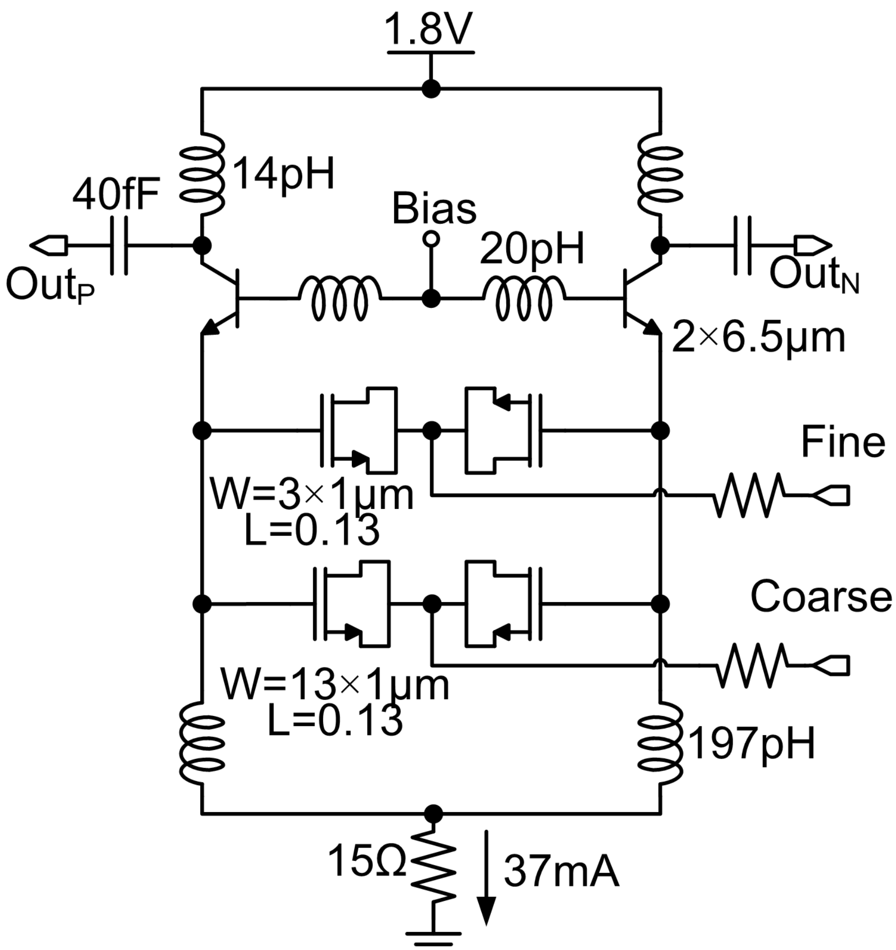


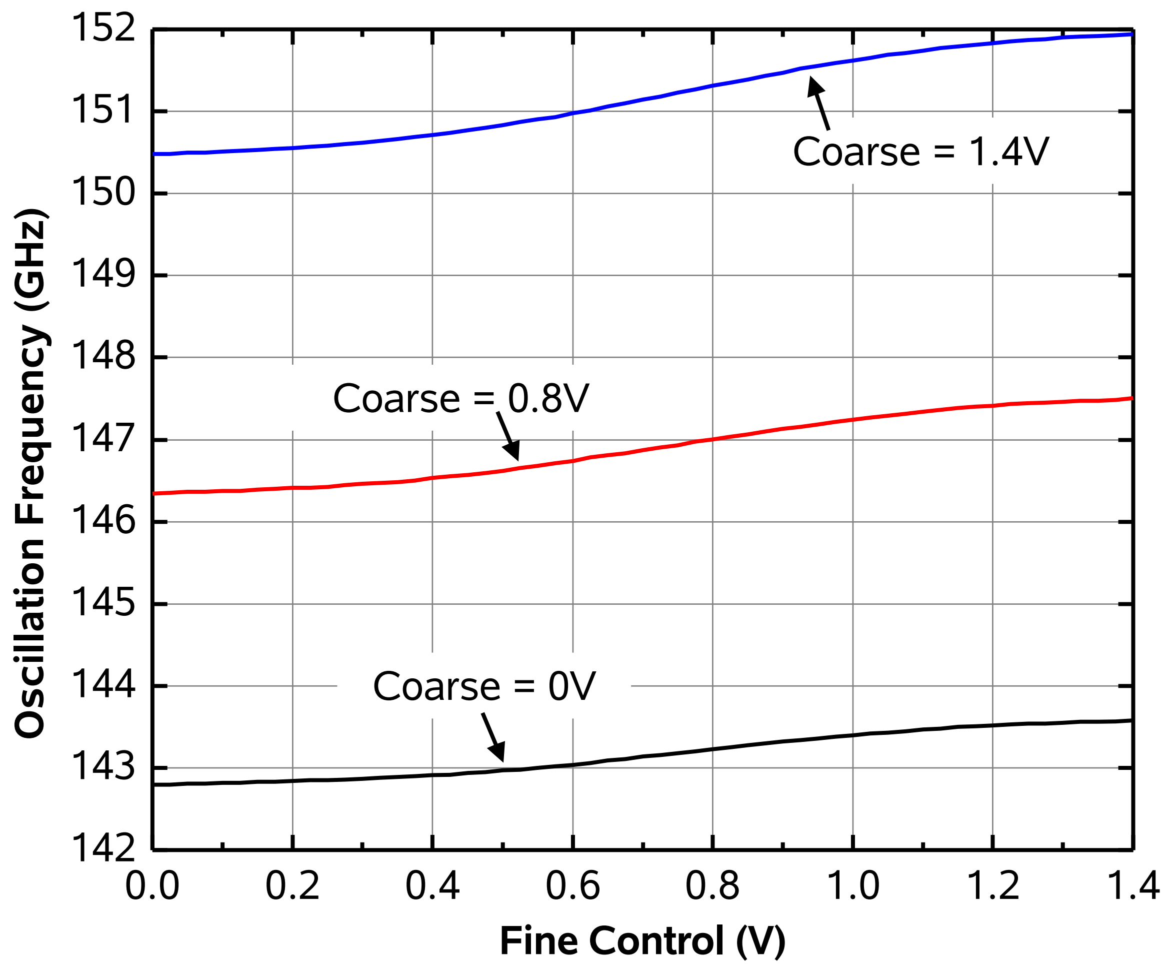






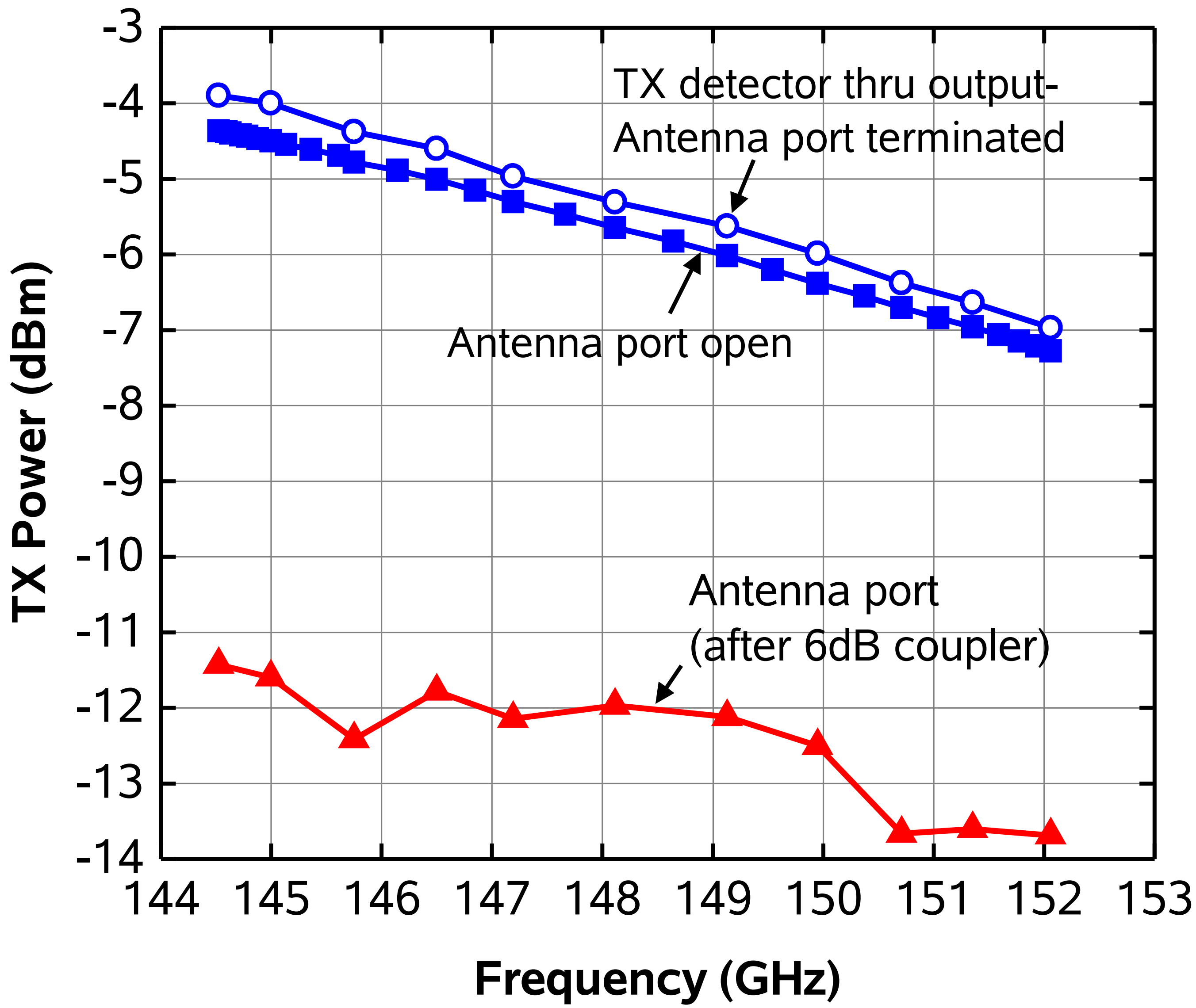
145 GHz Fundamental Frequency VCO





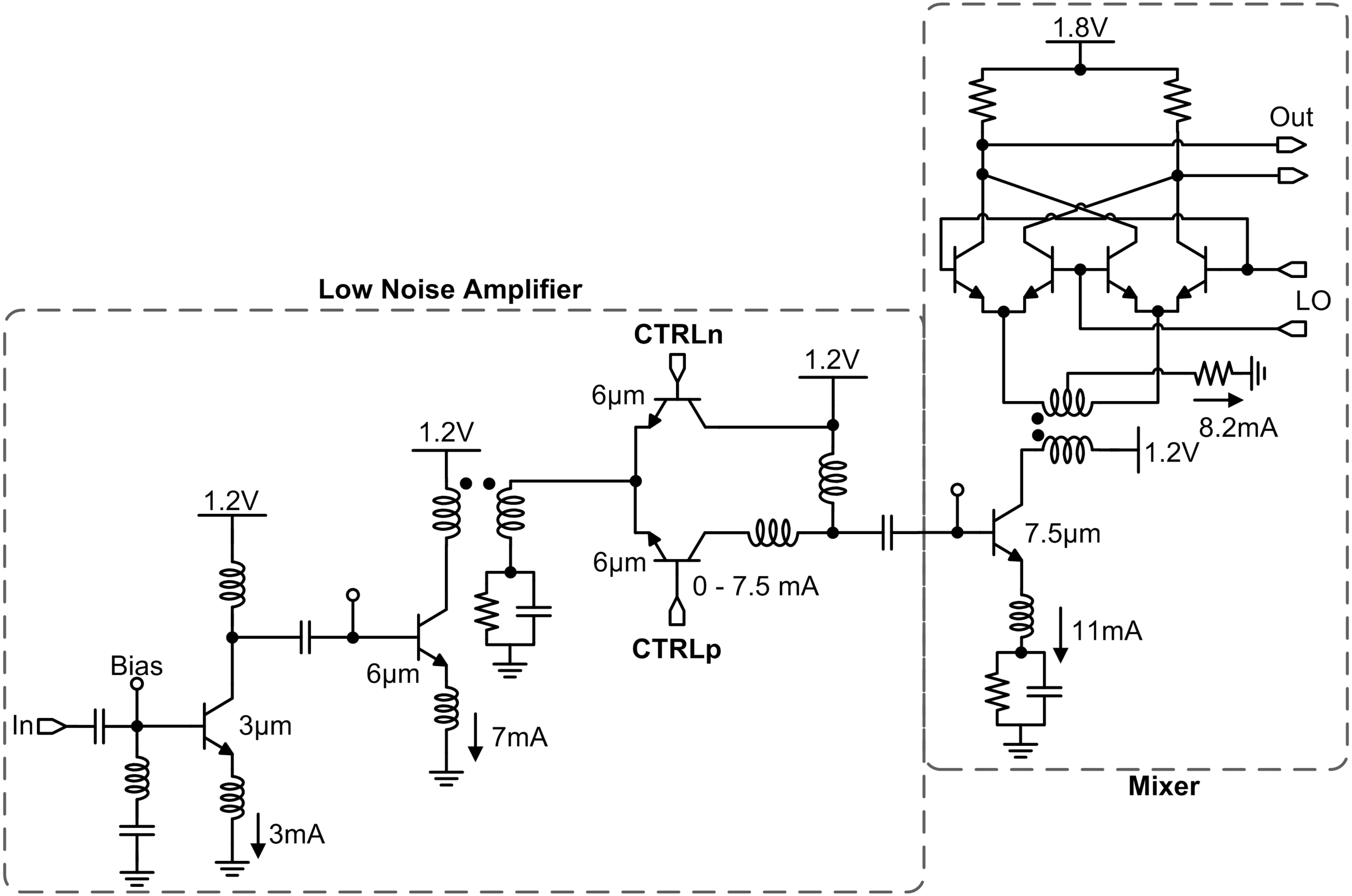
- 143-152 GHz tuning range
- PN=-103dBc/Hz @10MHz
- P_{DC} = 72 mW

Measured output power

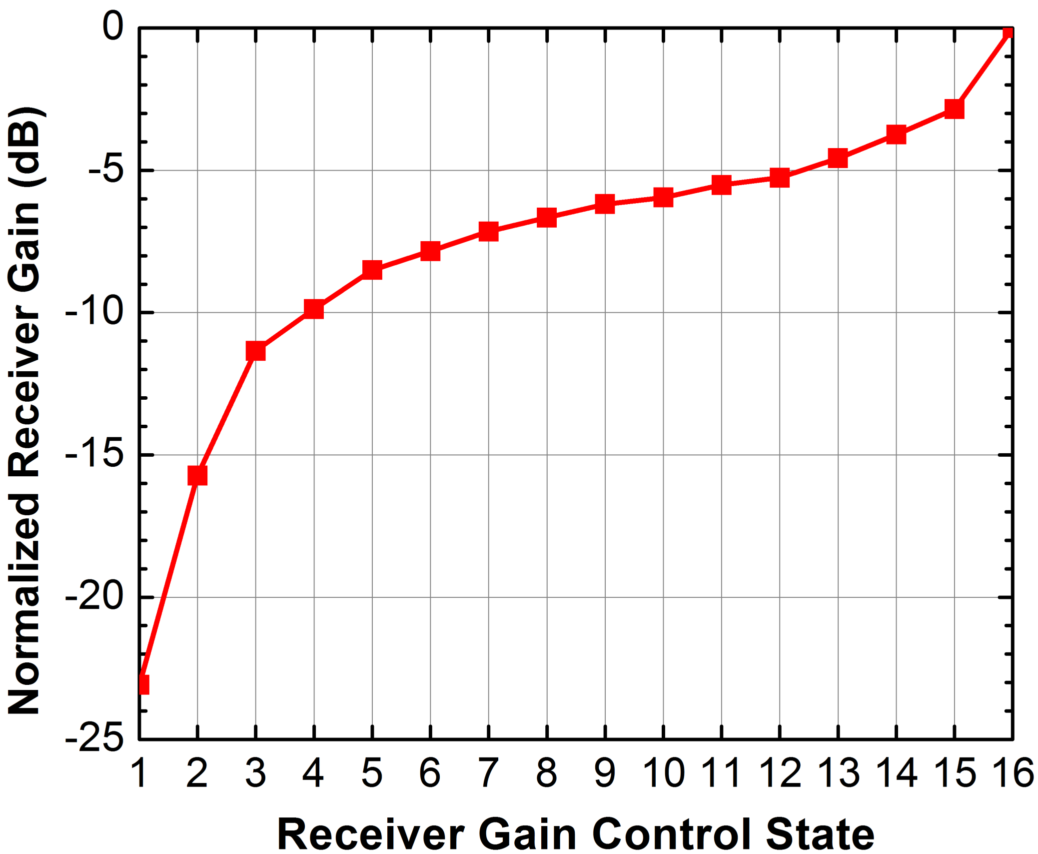


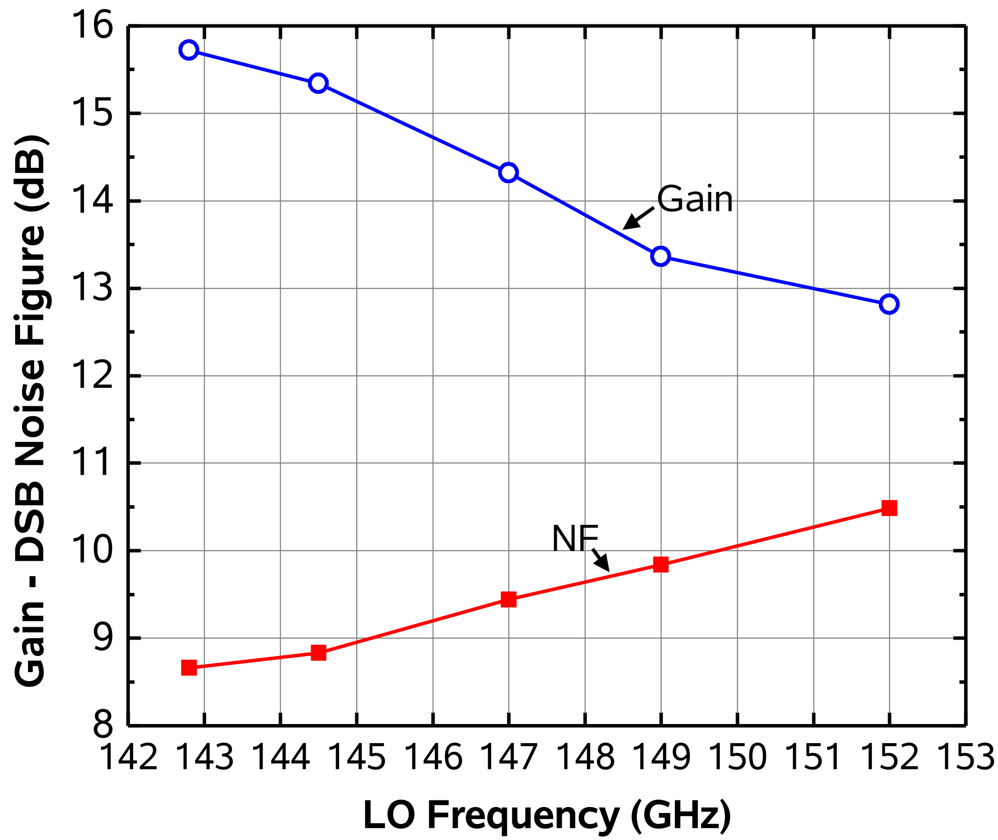
- Power at antenna port measured with ELVA power sensor
- On-chip and external measurements track very well

Receiver schematics



Receiver Gain and Noise Figure

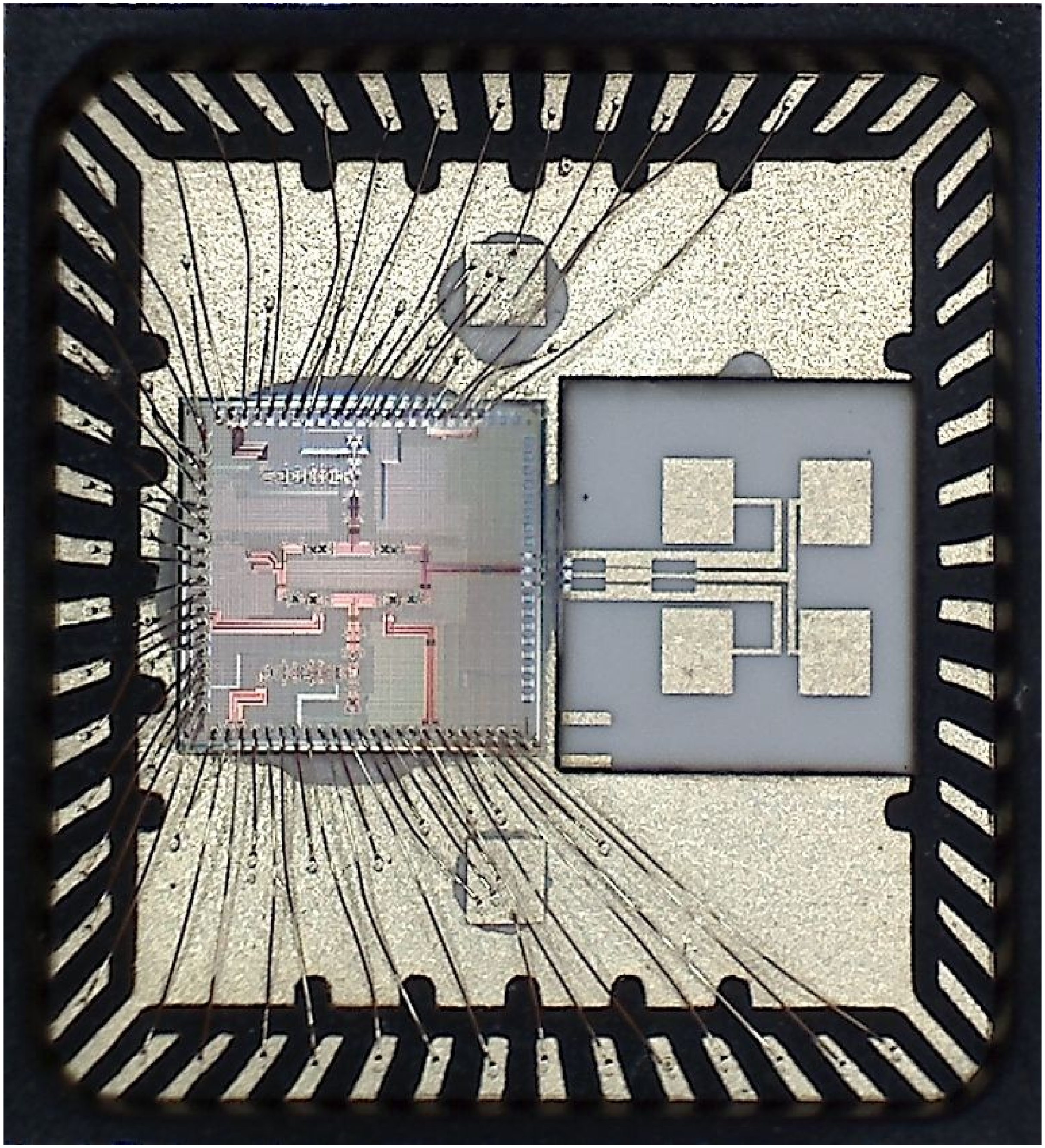




13-15 dB gain, 23 dB of gain control in LNA

Low noise figure: 8.5-10.5dB

Antenna and die in package



•QFN package with bondwire transition to antenna on alumina

Courtesy of Robert Bosch GmbH. Karlsruhe Institute of Technology and EU SUCCESS project partners

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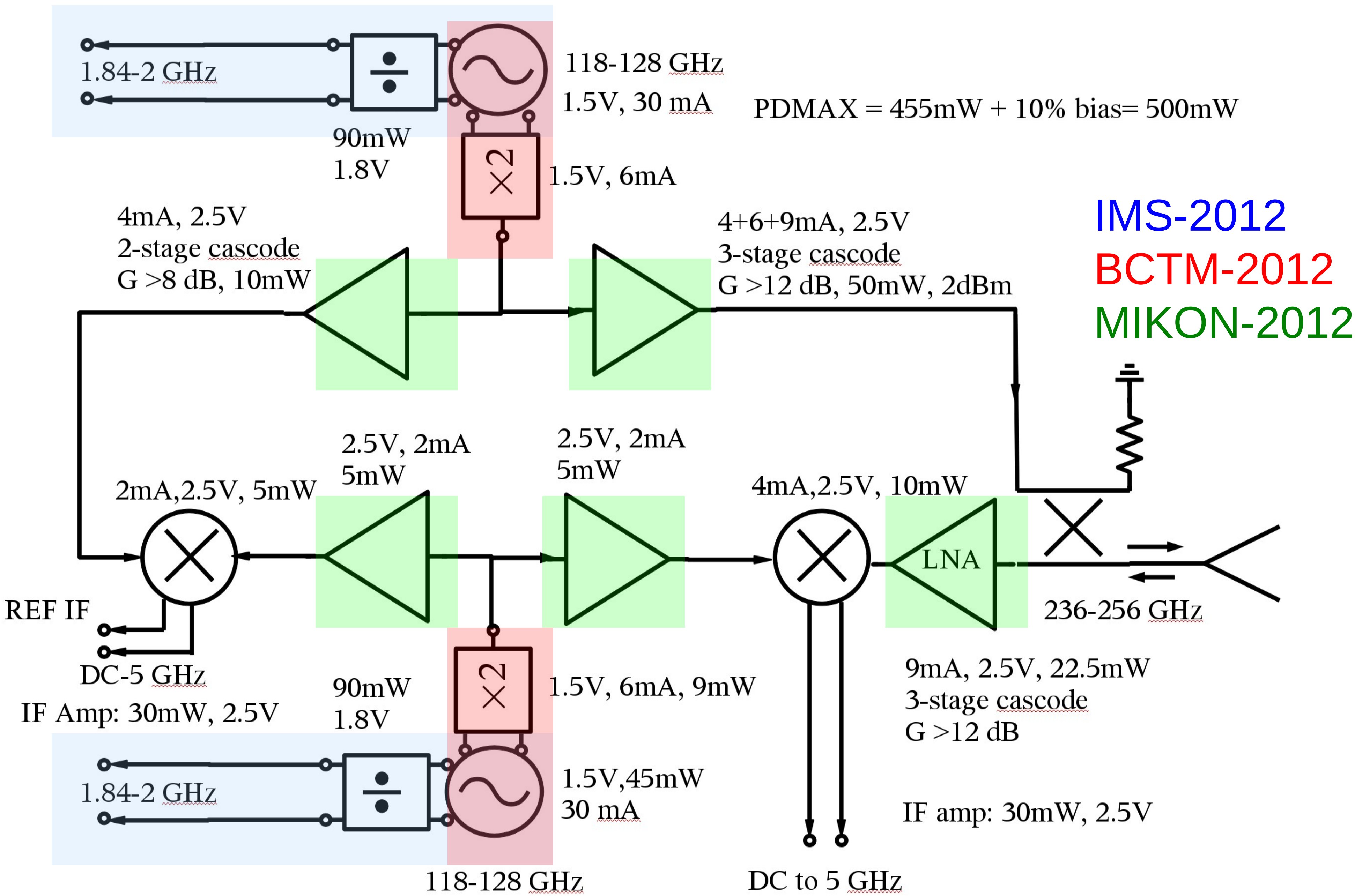
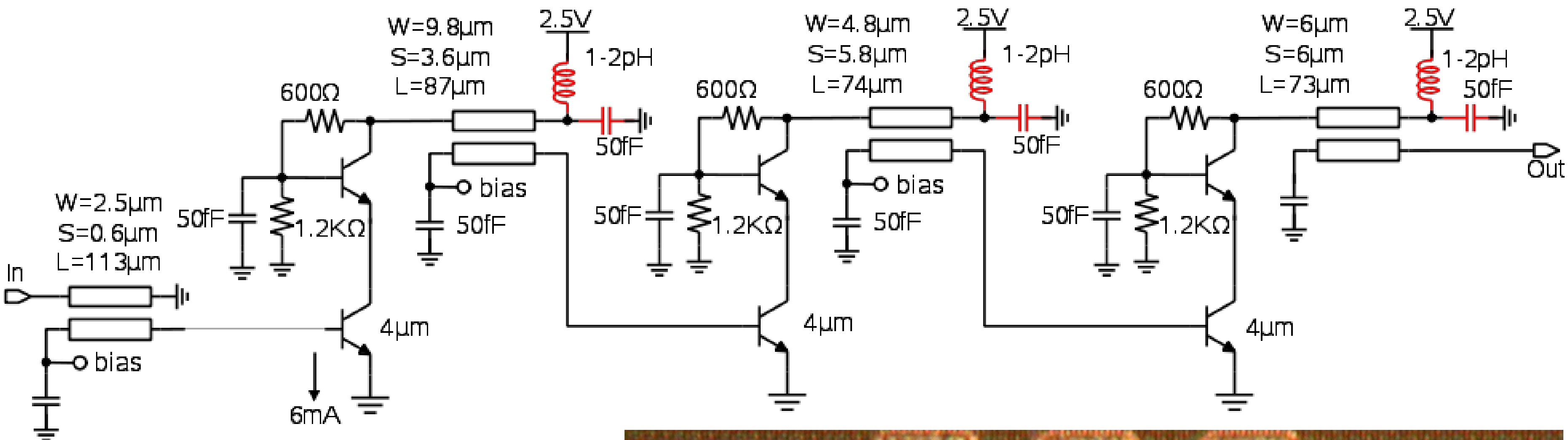
240-GHz Transceiver Blocks



240-GHz Amplifier

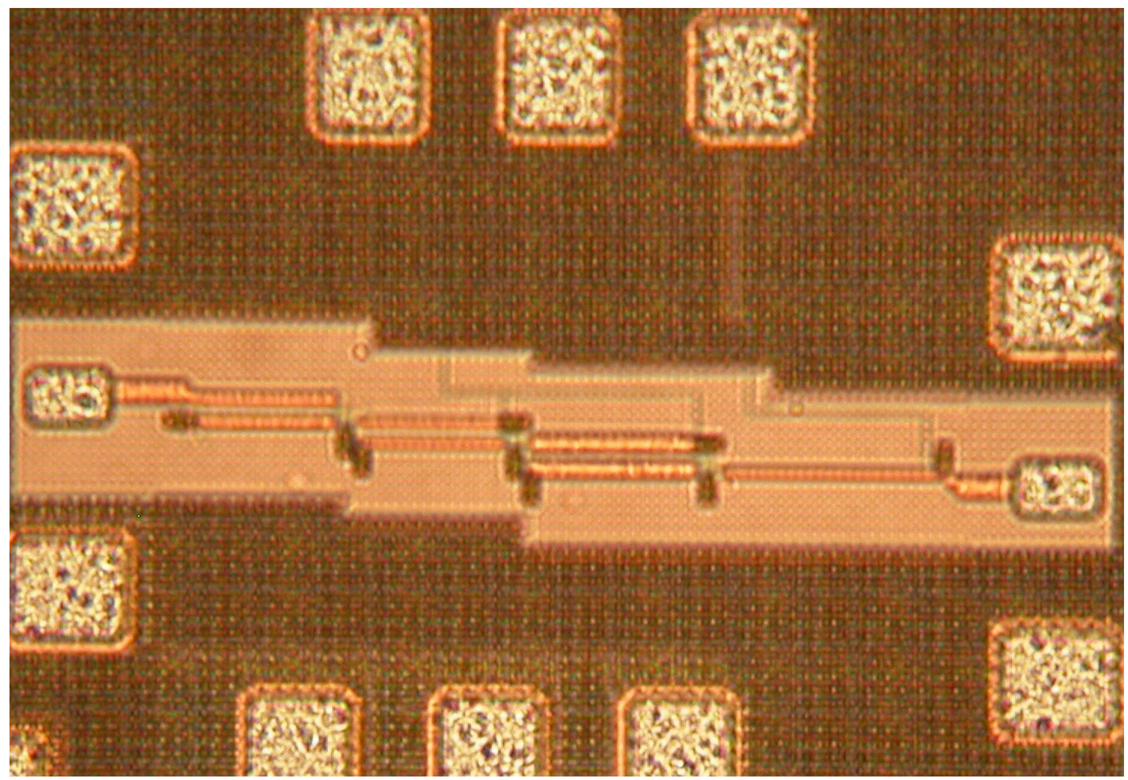


SiGe HBT 300/400 GHz

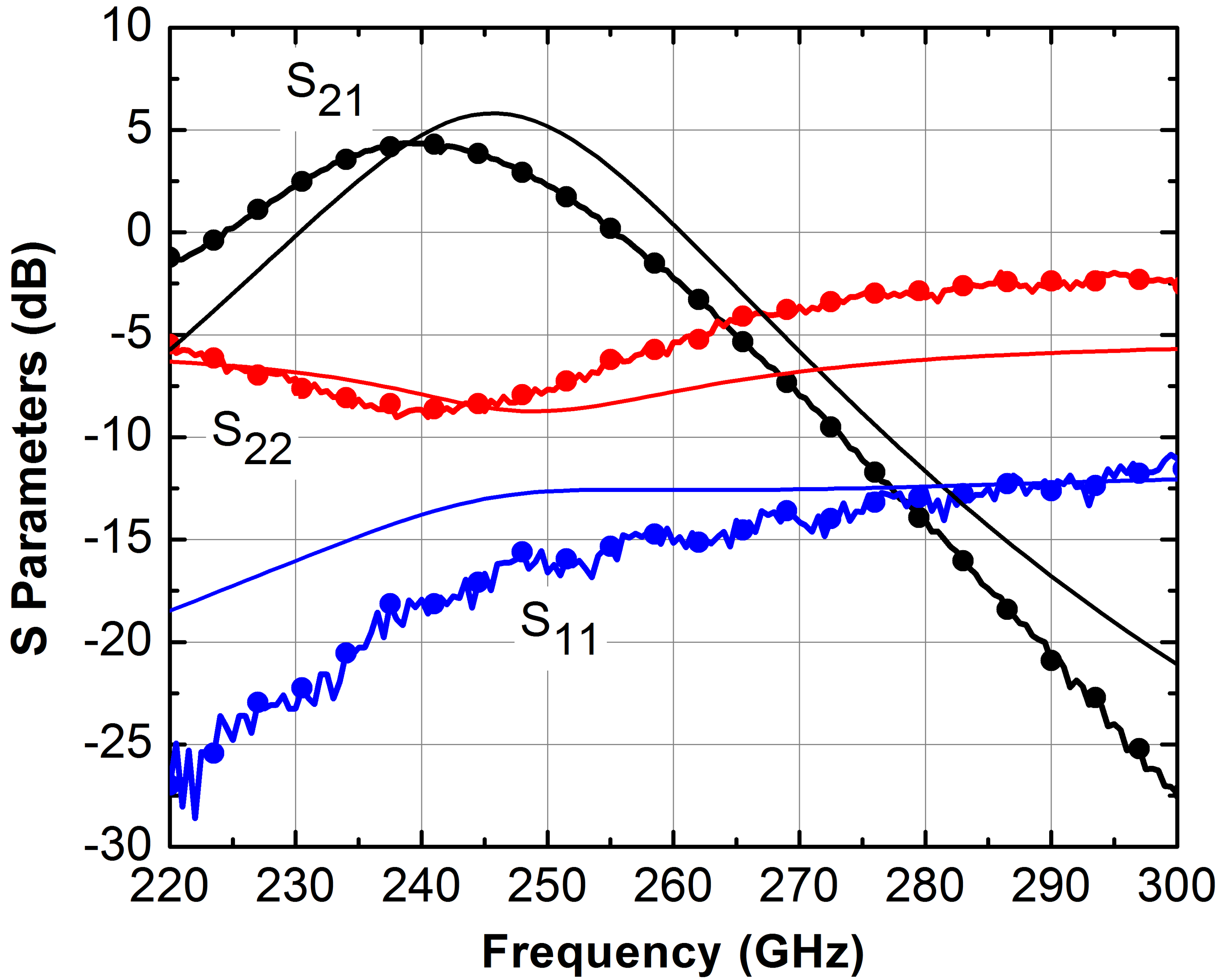
P_D = 37.5 mW

G = 4.5 dB @ 240 GHz

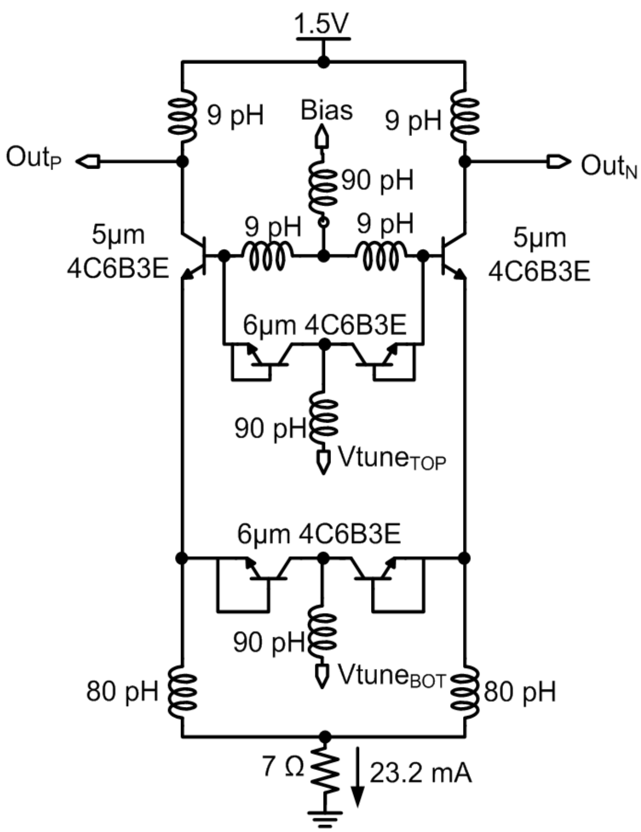
[I. Sarkas et al, MIKON 2012]



Measurements vs. sims



VCO Topology & Design



150-GHz VCO [Balteanu et al. IMS2012]

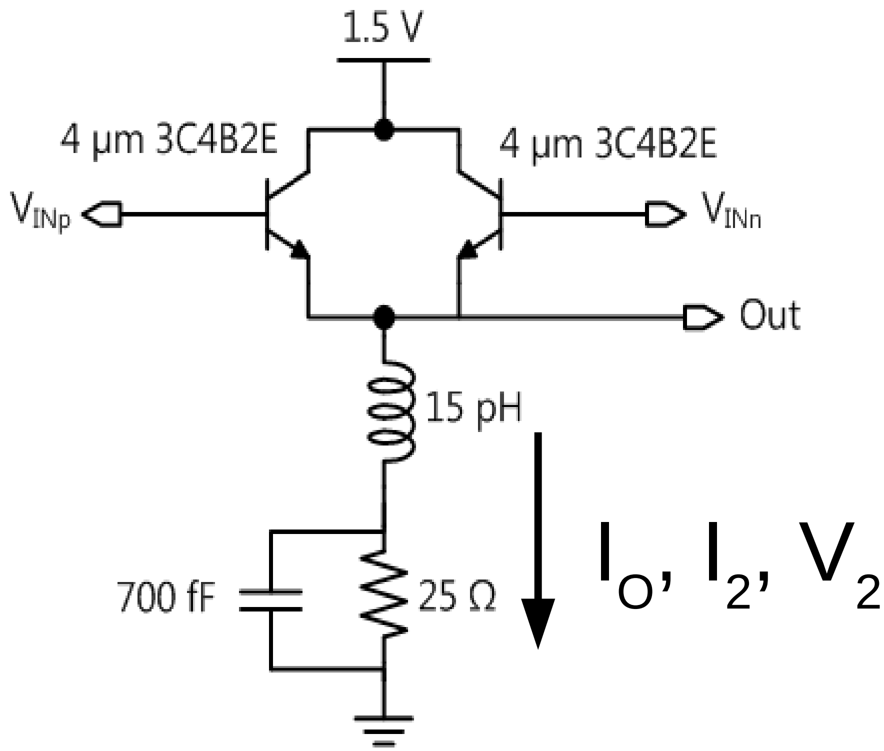
Topology

- Colpitts-Clapp for tuning [Pohl et al., CSICS 2008]
- $L_C \approx L_B$ for best performance
- L for bias noise filtering
- Colpitts above 200 GHz
- No MiM cap across BE junction
- HBT varactors (no AMOS)

Design (at 125 °C)

- Textbook: Based on small-signal sims of Z(f)
- Large signal verification

Multiplier Design Methodology



- Textbook Class-B PA-like design [S. Maas]
- EF output for VCO buffering
- $t_0/T = 118^0$
- $J_{MAX} = 24\ mA/\mu m^2$,

$$\eta_{DC} = \left| \frac{\cos\left(n\pi \frac{t_0}{T}\right)}{1-\left(2n\frac{t_0}{T}\right)^2} \right| = 0.6488$$

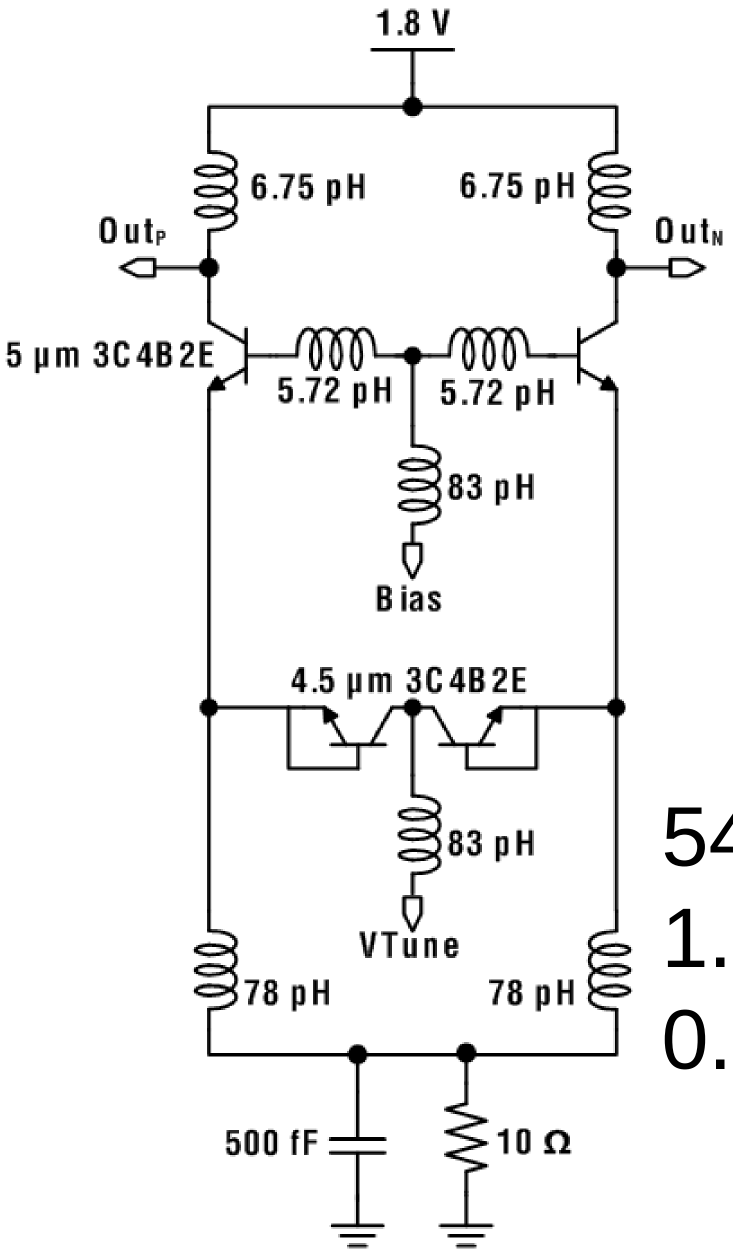
$$I_2 = 2 \cdot I_{MAX} \frac{4t_0}{\pi T} \left| \frac{\cos\left(2\pi \frac{t_0}{T}\right)}{1-\left(4\frac{t_0}{T}\right)^2} \right| = 12.5\,mA$$

$$P_L = \frac{V_2 \cdot I_2}{2} = 1.89\,mW$$

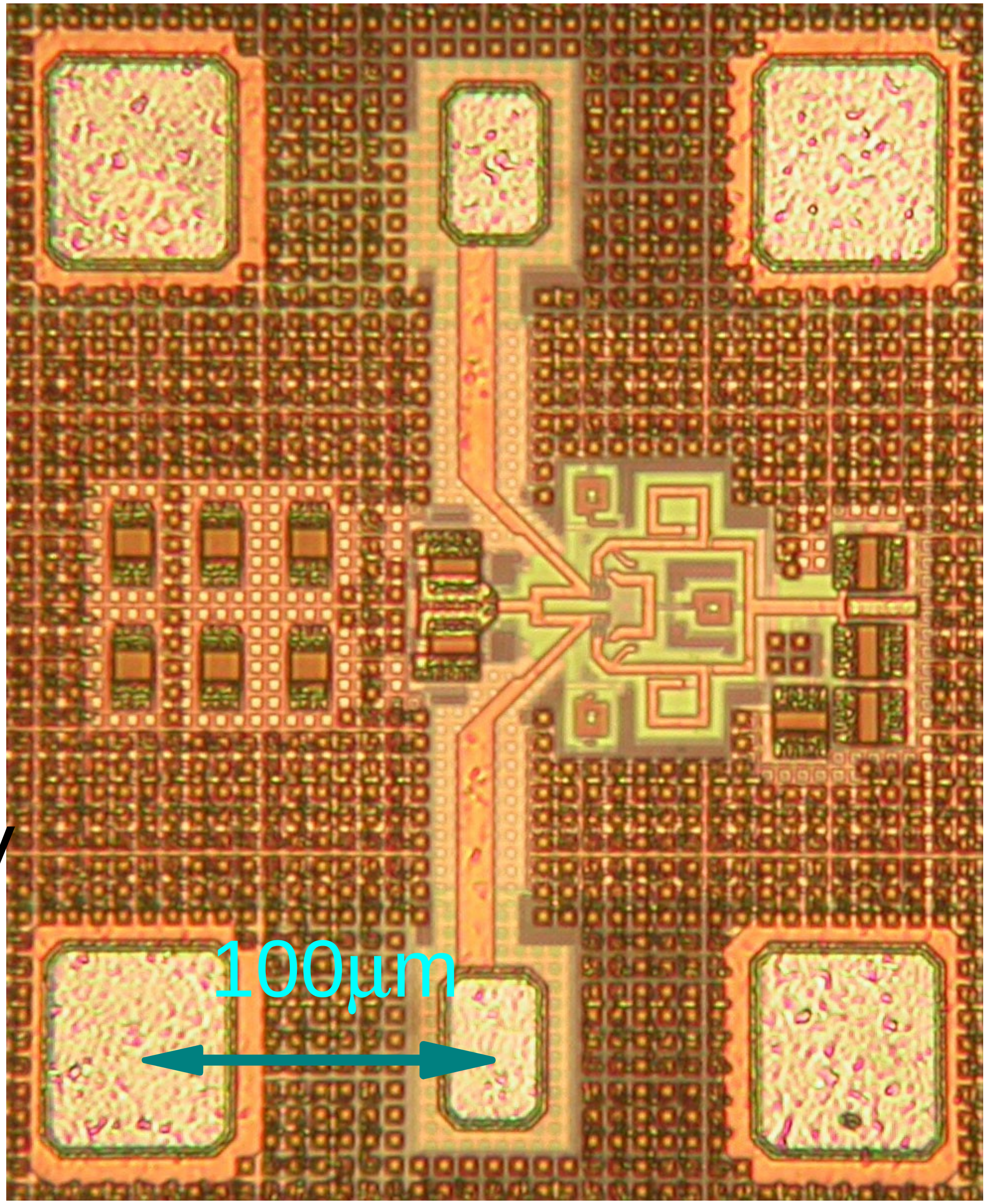
$$I_0 = 2 \cdot I_{MAX} \frac{2t_0}{\pi T} = 9.7\,mA.$$

$$R_{LOPT} = \frac{V_2}{I_2} = \frac{0.3}{12.5\,m} = 23.88\,Ohm.$$

240-GHz VCO

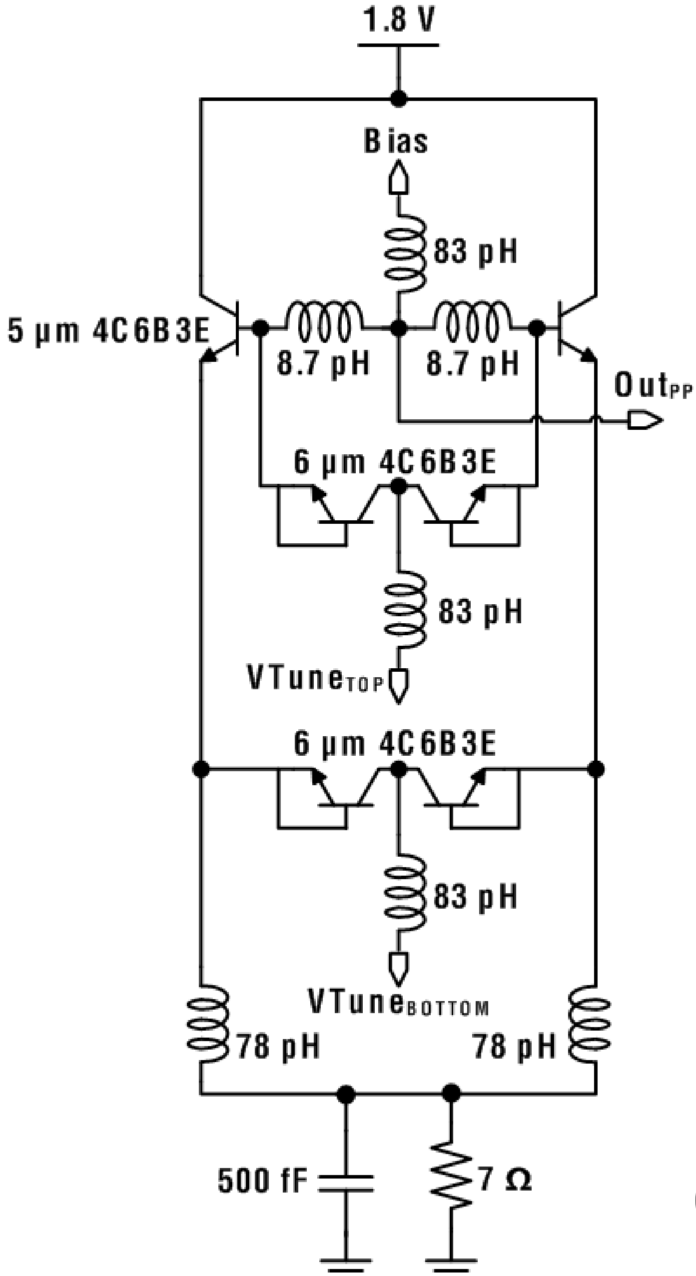


54 mW
1.5-1.8V
0.8%

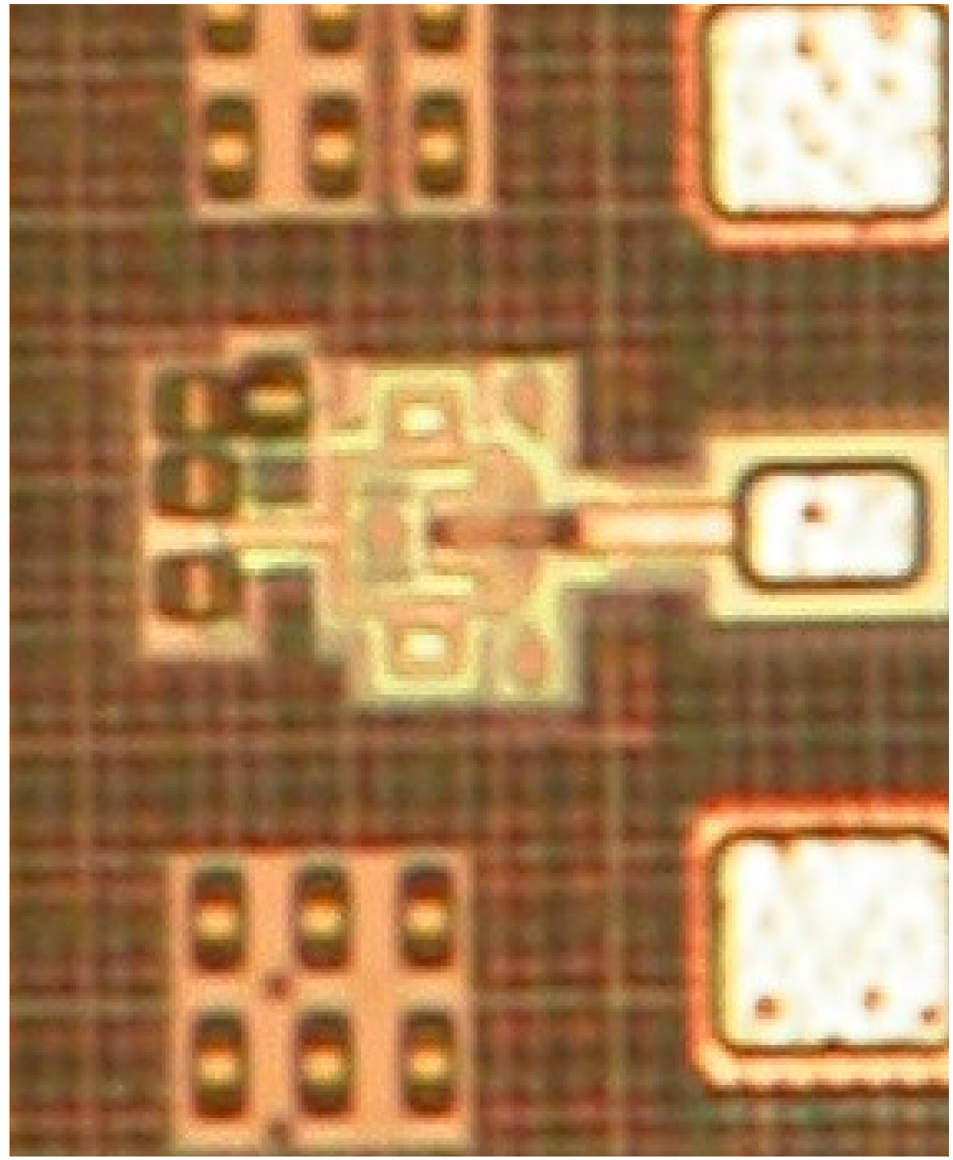


[A. Tomkins et al, BCTM 2012]

320-GHz Push-Push VCO

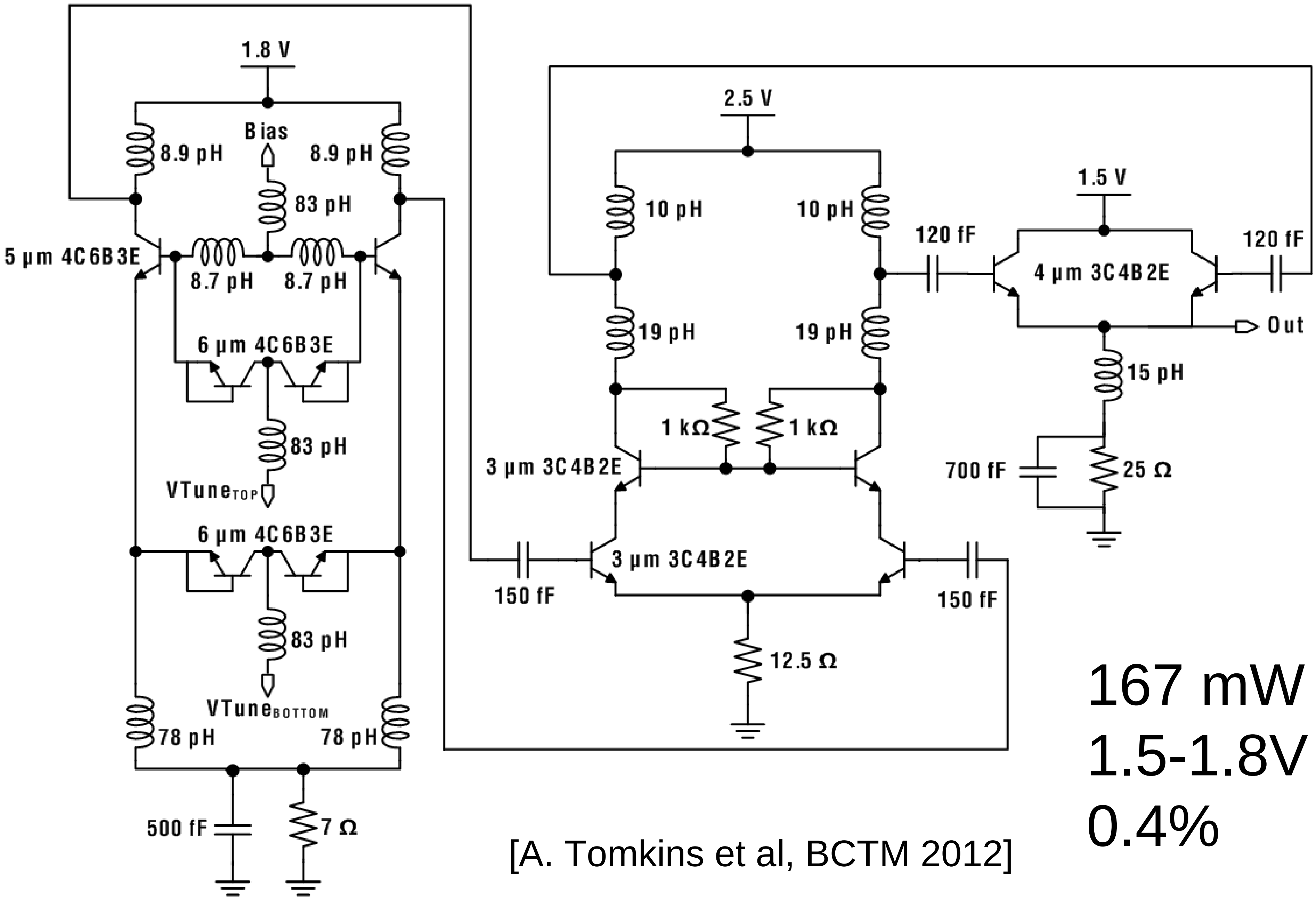


63 mW
1.5-1.8V
0.07%



[A. Tomkins et al, BCTM 2012]

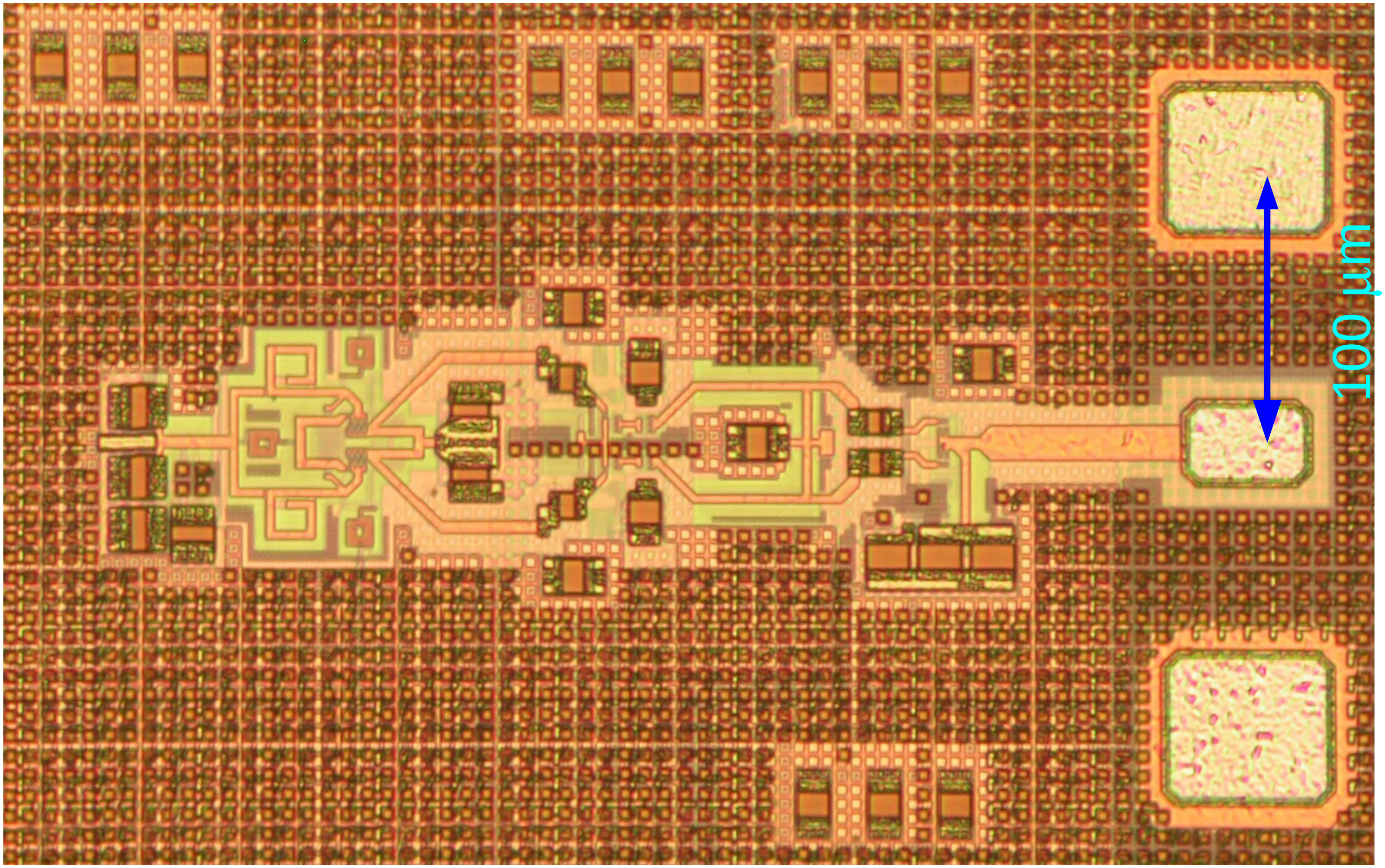
300-GHz VCO+Buffer+Doubler



[A. Tomkins et al, BCTM 2012]

167 mW
1.5-1.8V
0.4%

Layout



200+ GHz Signal Source Test Methodology

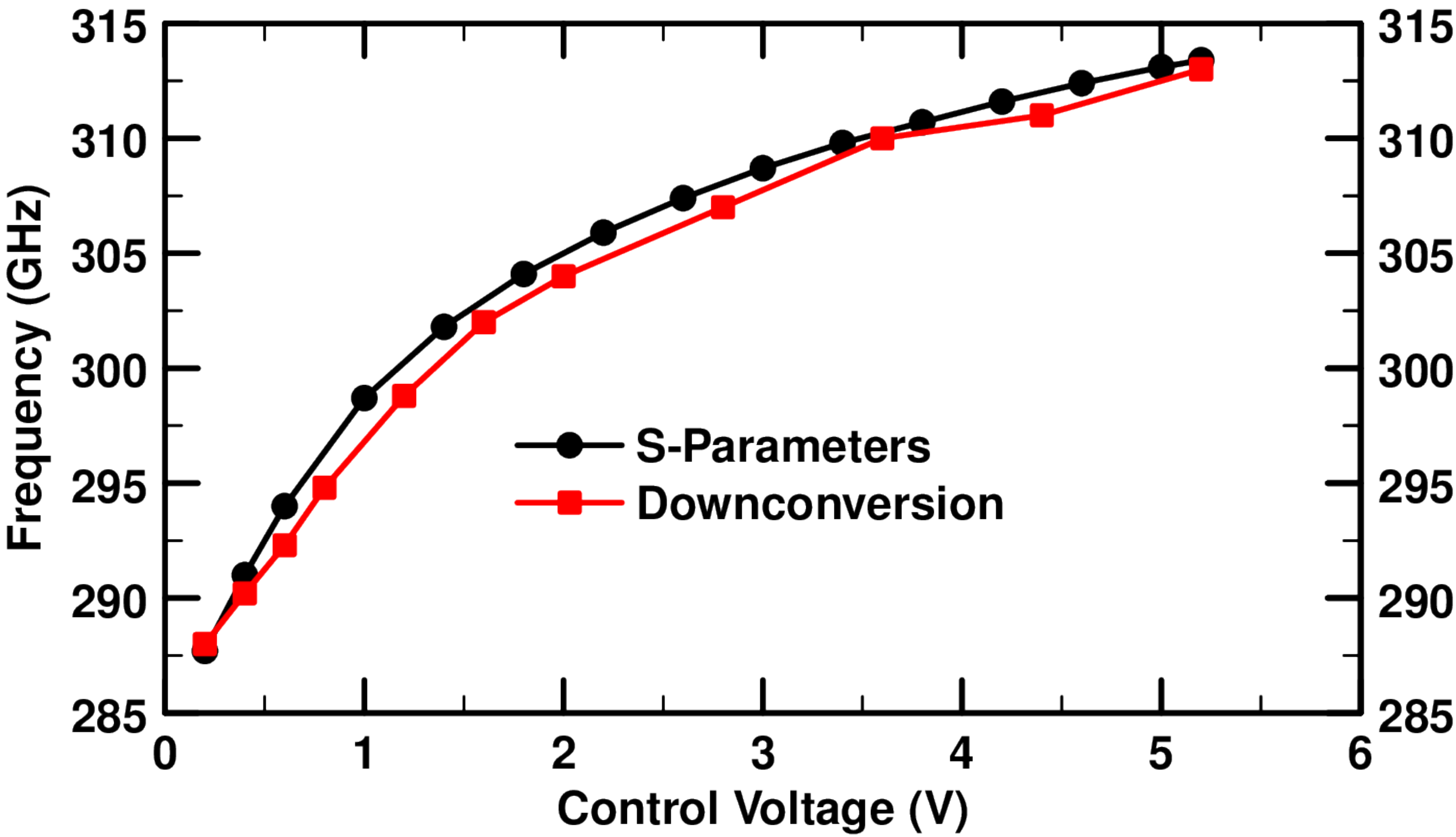
- S-parameters for $f_{OSC}(V)$ from regions where S_{11}>0 dB

  [K. Yau et al., IEEE Micro, Feb. 2012]

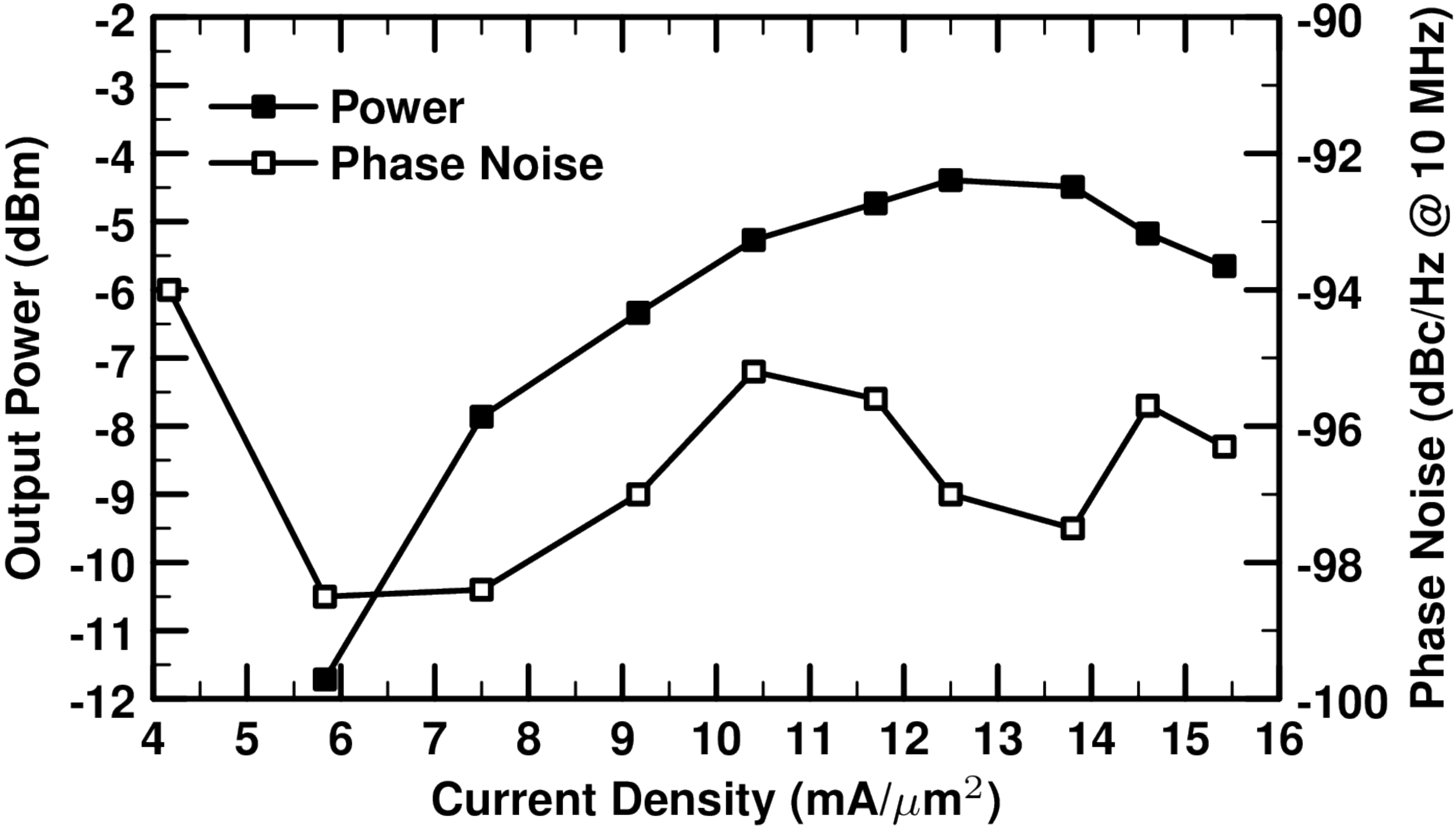
- VNA downconverter to 300 MHz IF and PSA for tuning range and phase noise

- Erikson calorimeter for P_{out} vs. control voltage

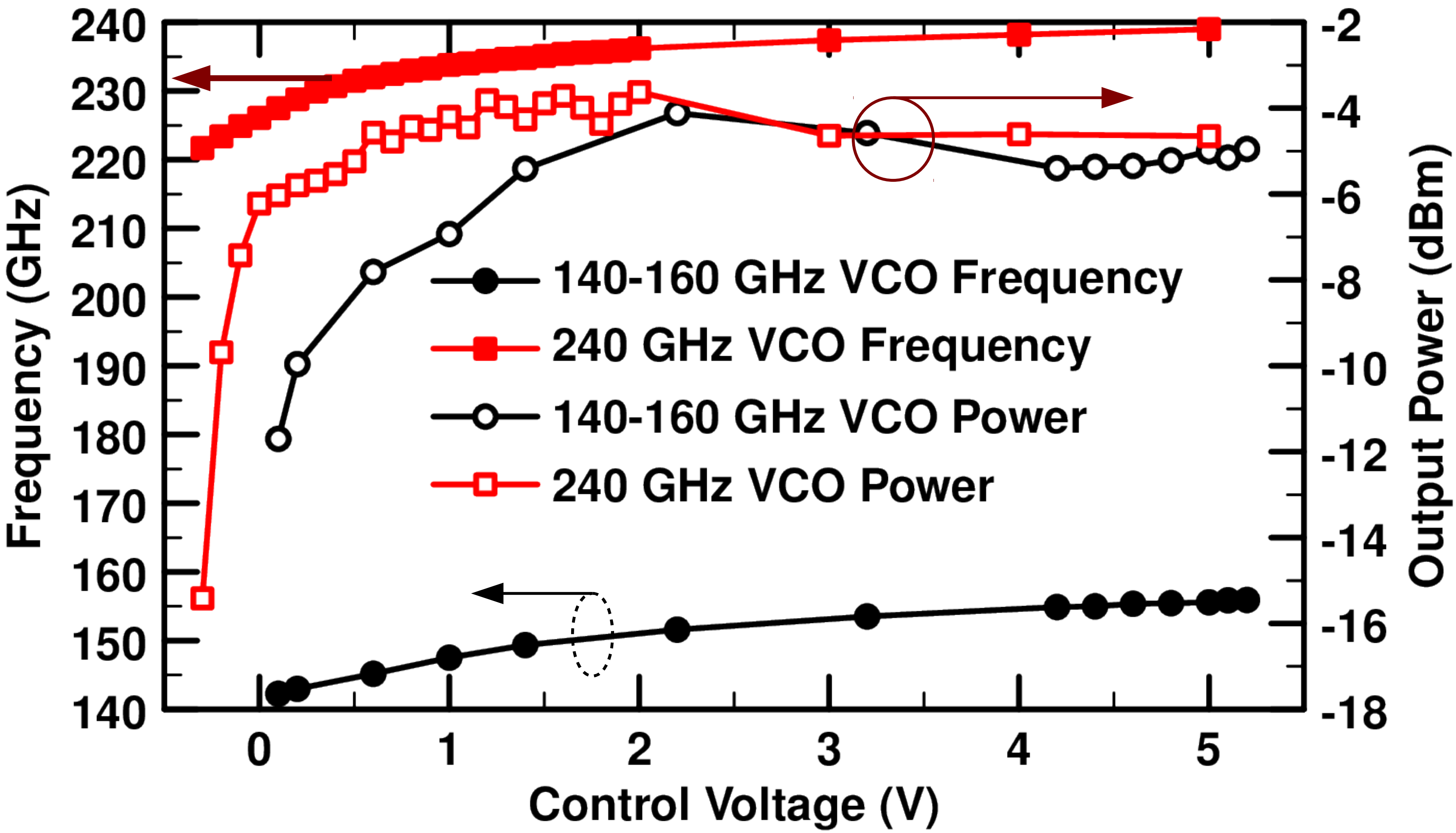
Tuning Range: S-Params/Spectrum



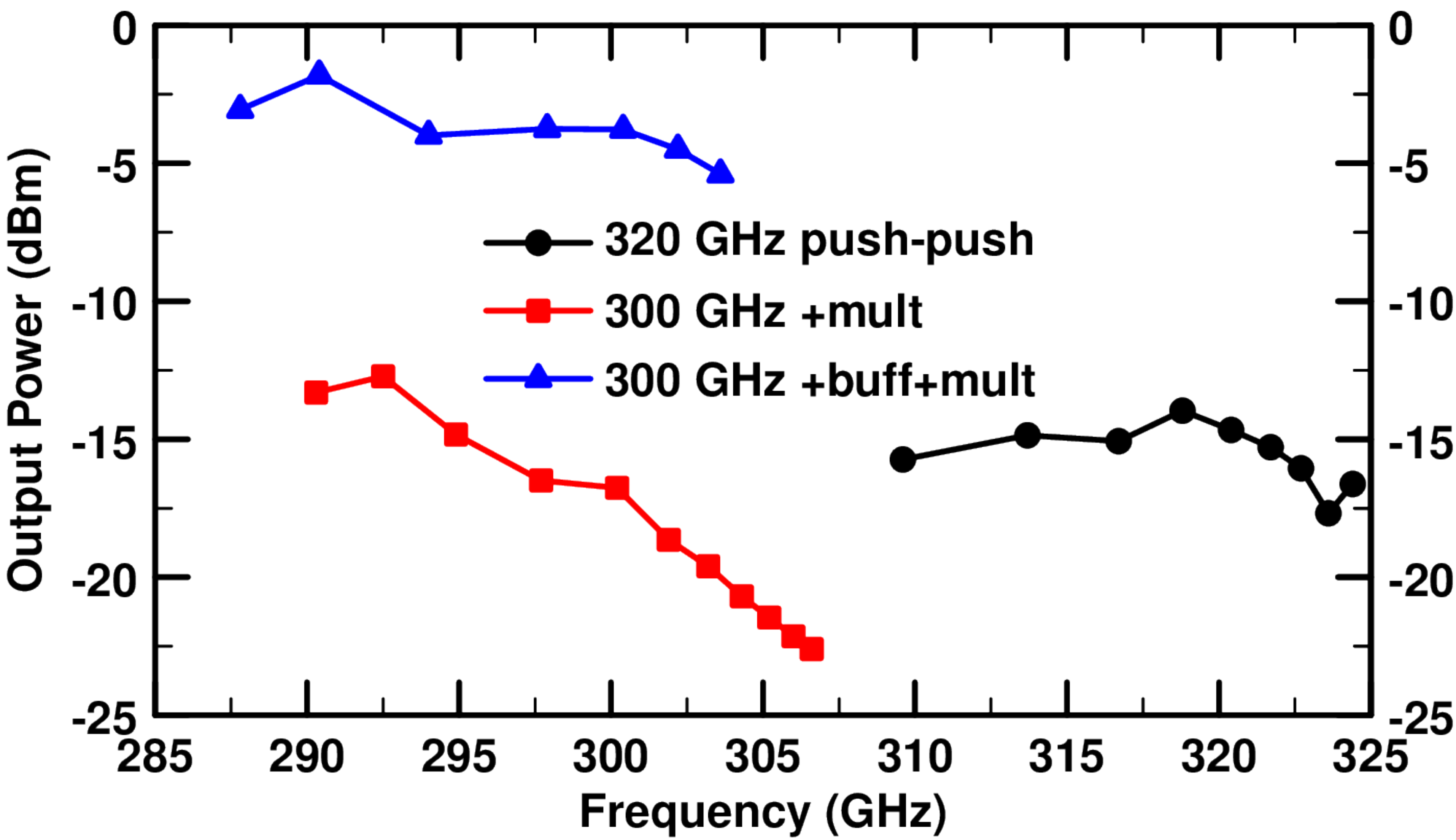
240-GHz VCO Phase Noise and P_{OUT}



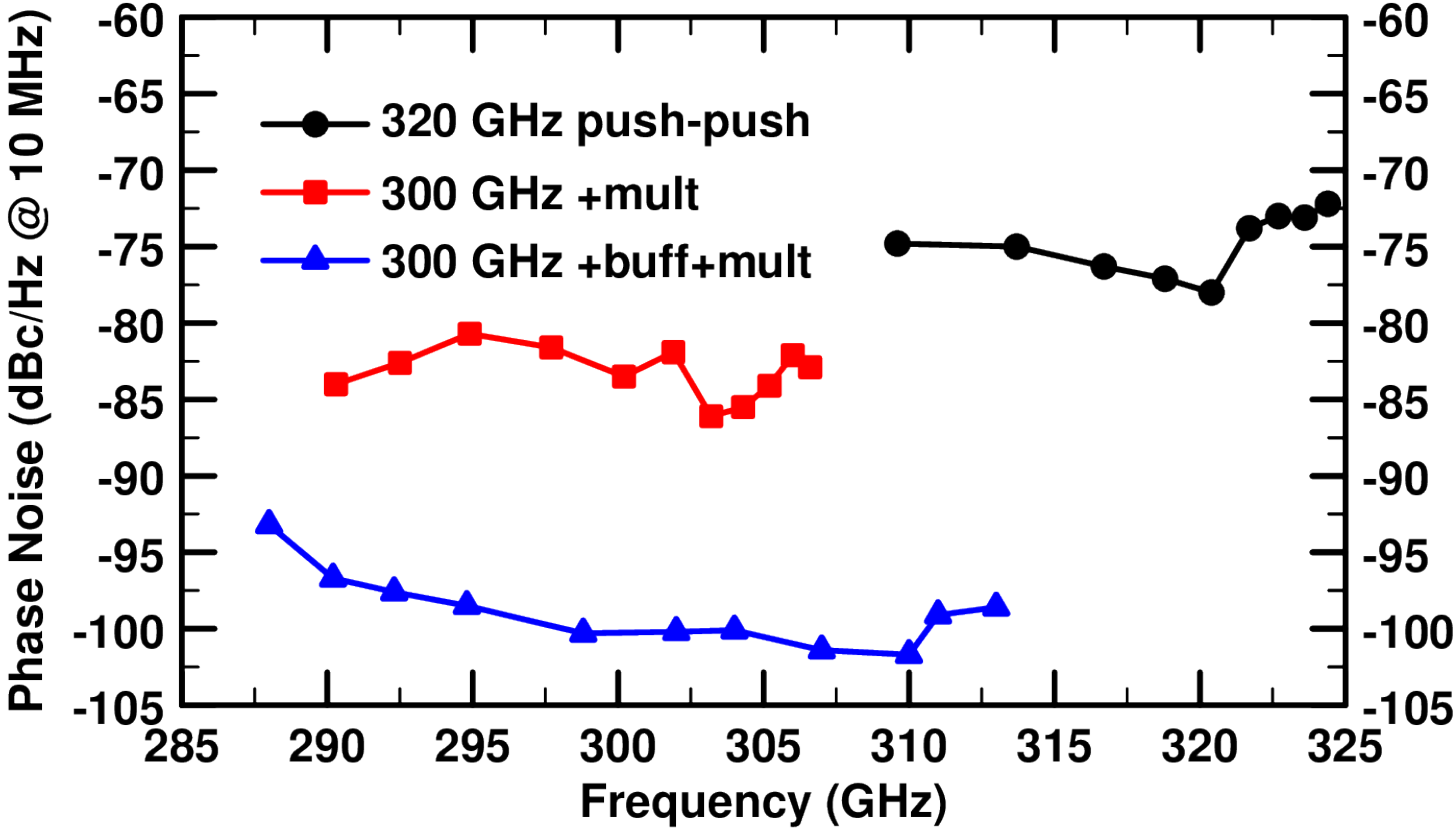
150/240 GHz VCO Comparison



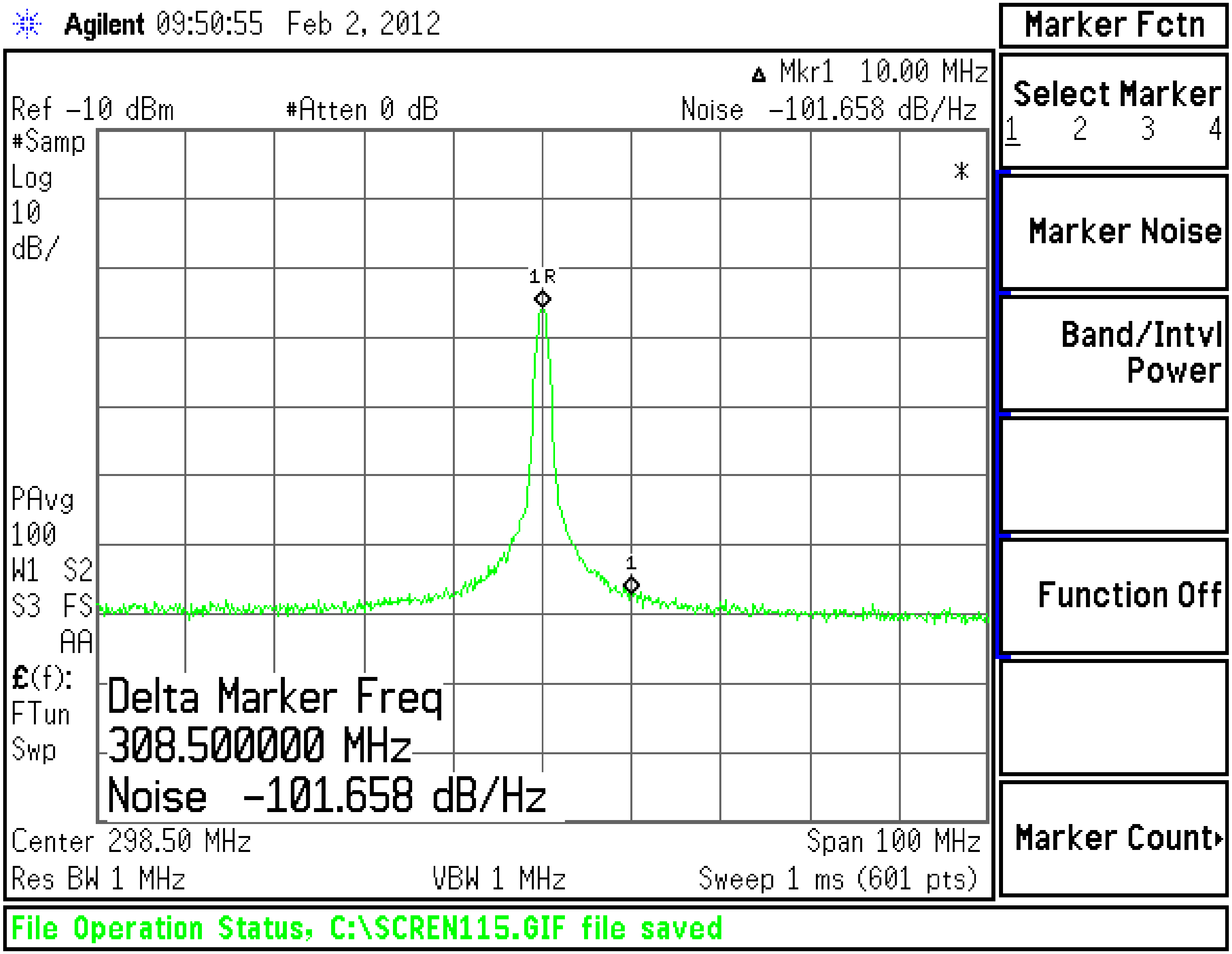
300-GHz Signal Source Comparison



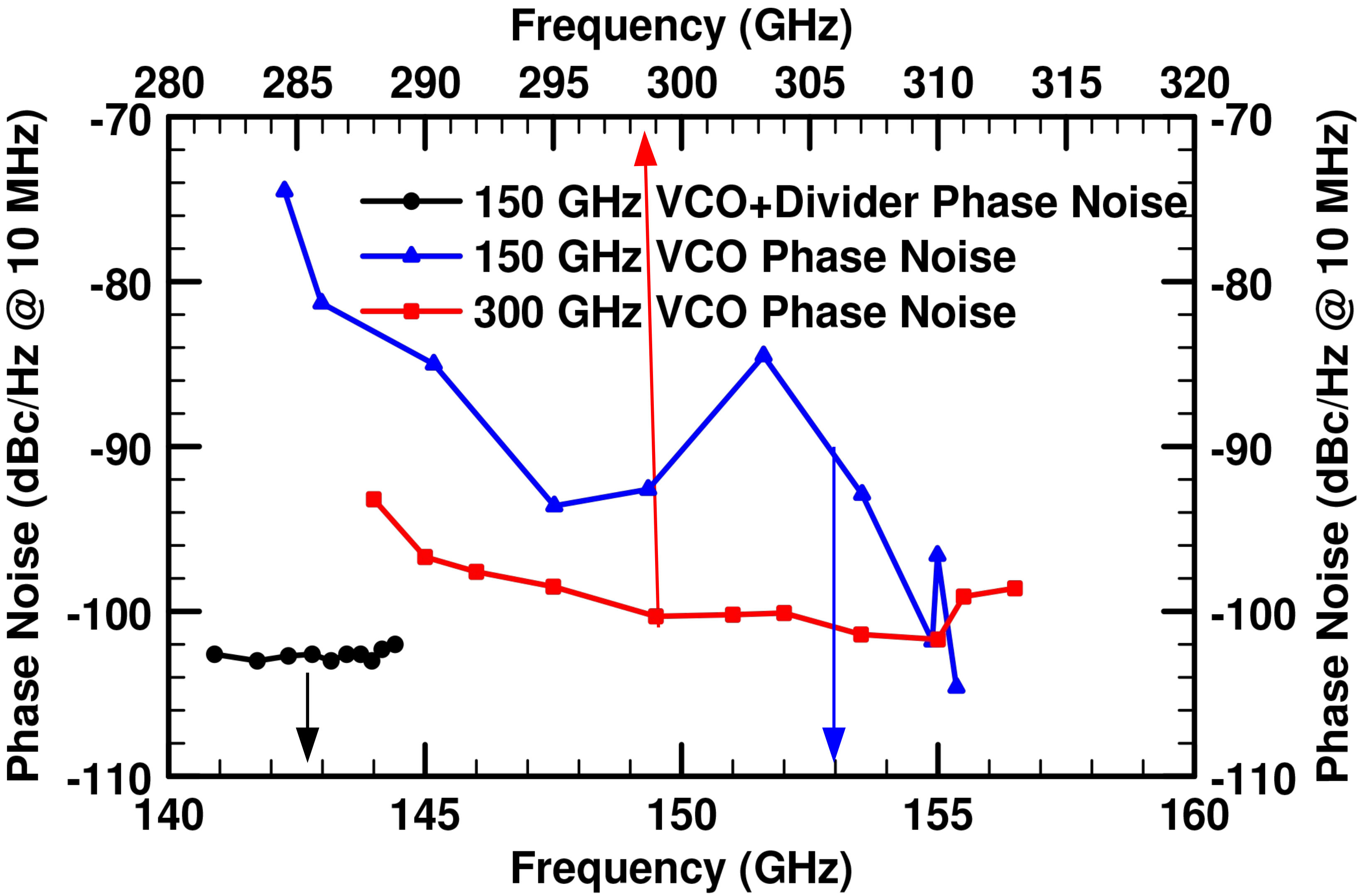
300-GHz Signal Source Comparison (ii)



Phase Noise of VCO-doubler at 309 GHz



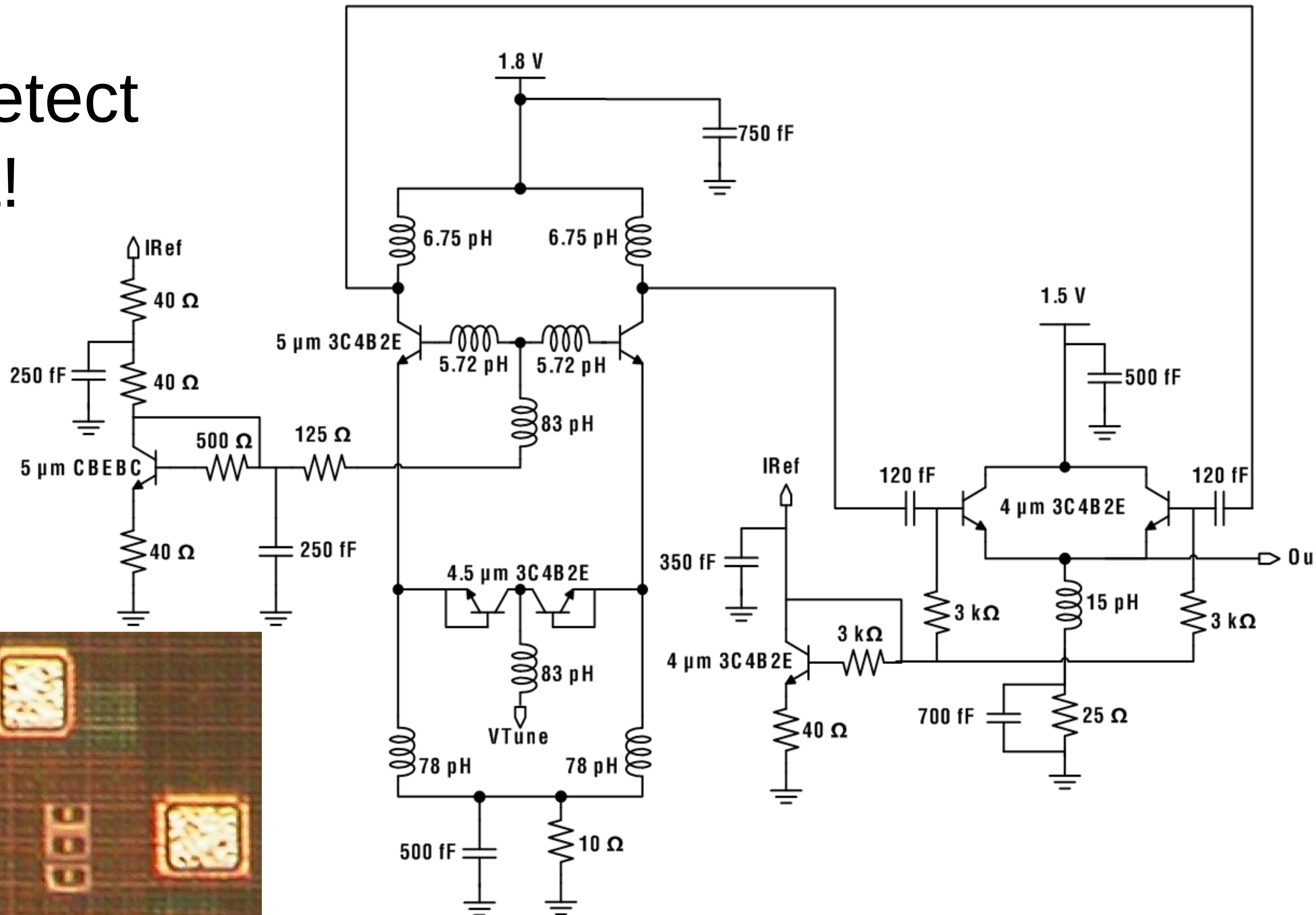
300-GHz vs. 150-GHz Phase Noise

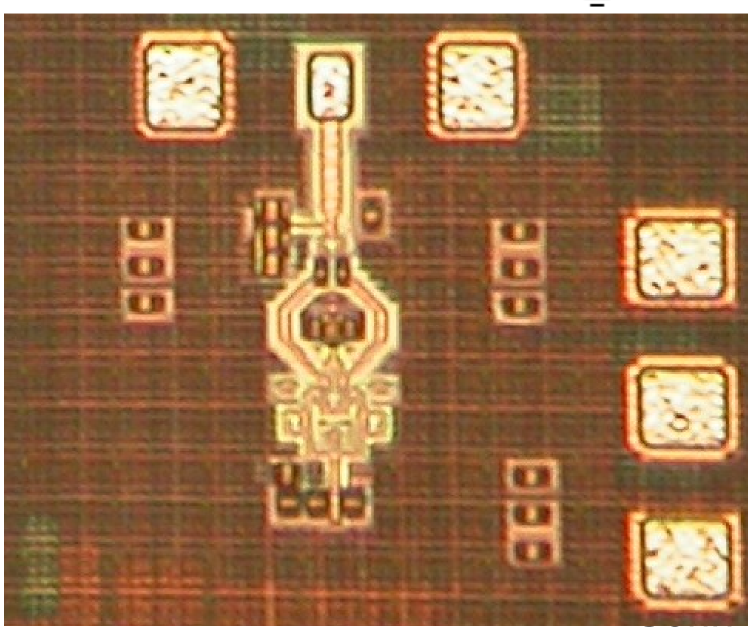


SAME VCO in BOTH!

480-GHz source: VCO+doubler

Did not detect signal yet!

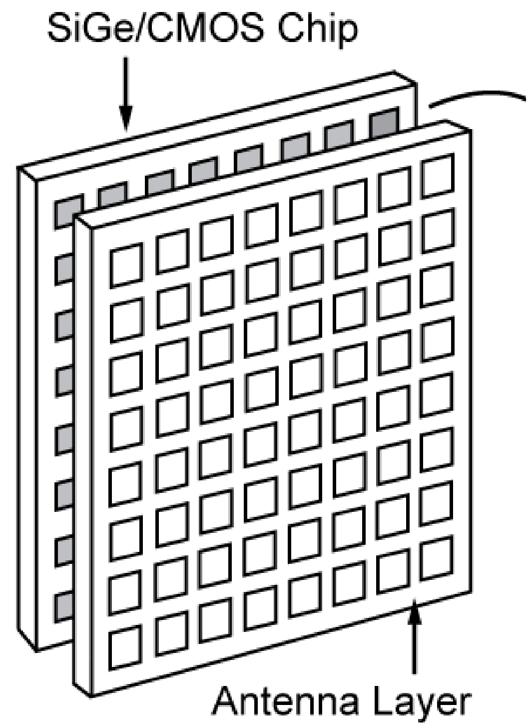




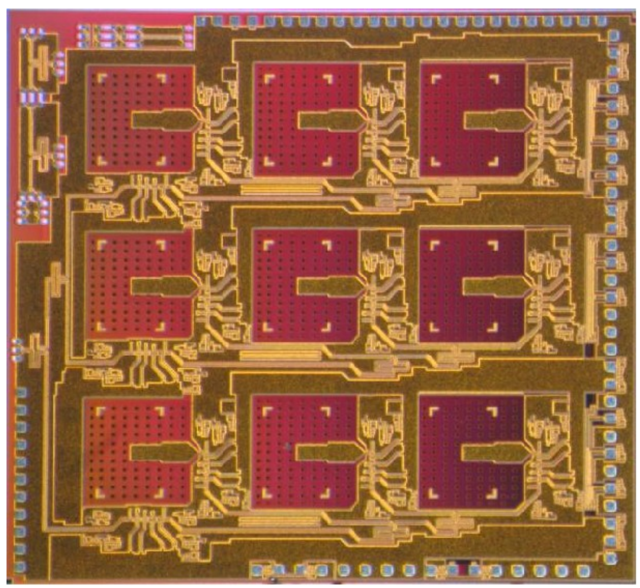
Conclusions

- D-Band Push-push & fundamental frequency transceivers
- On-die and in-package antennas
- 240-GHz fundamental VCO in SiGe
- Lowest phase noise 300-GHz signal source
- Buffer between VCO and doubler is critical
- 240-300 GHz transceiver feasible in 55-nm SiGe BiCMOS

Why 100-300 GHz?



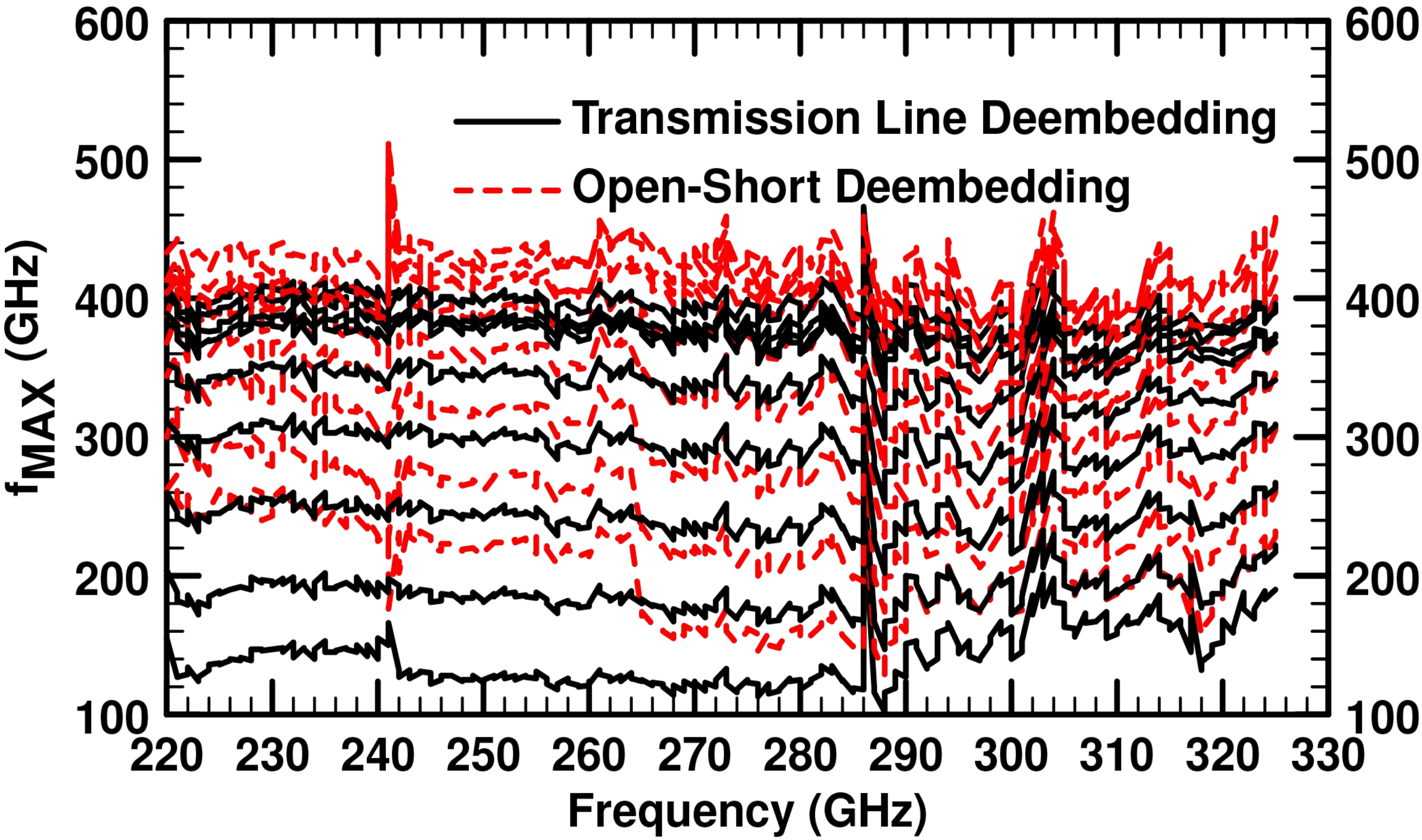
- Silicon transistors with f_{MAX}>400 GHz
- Smaller wavelengths: high res, high BW
- Small antenna size with good gain
- Lower power LNA, mixer, receiver
- But…
  - higher power PLL,
  - reduced P_{out},
  - shorter range ~$1/f^2$ or ~$1/f^4$



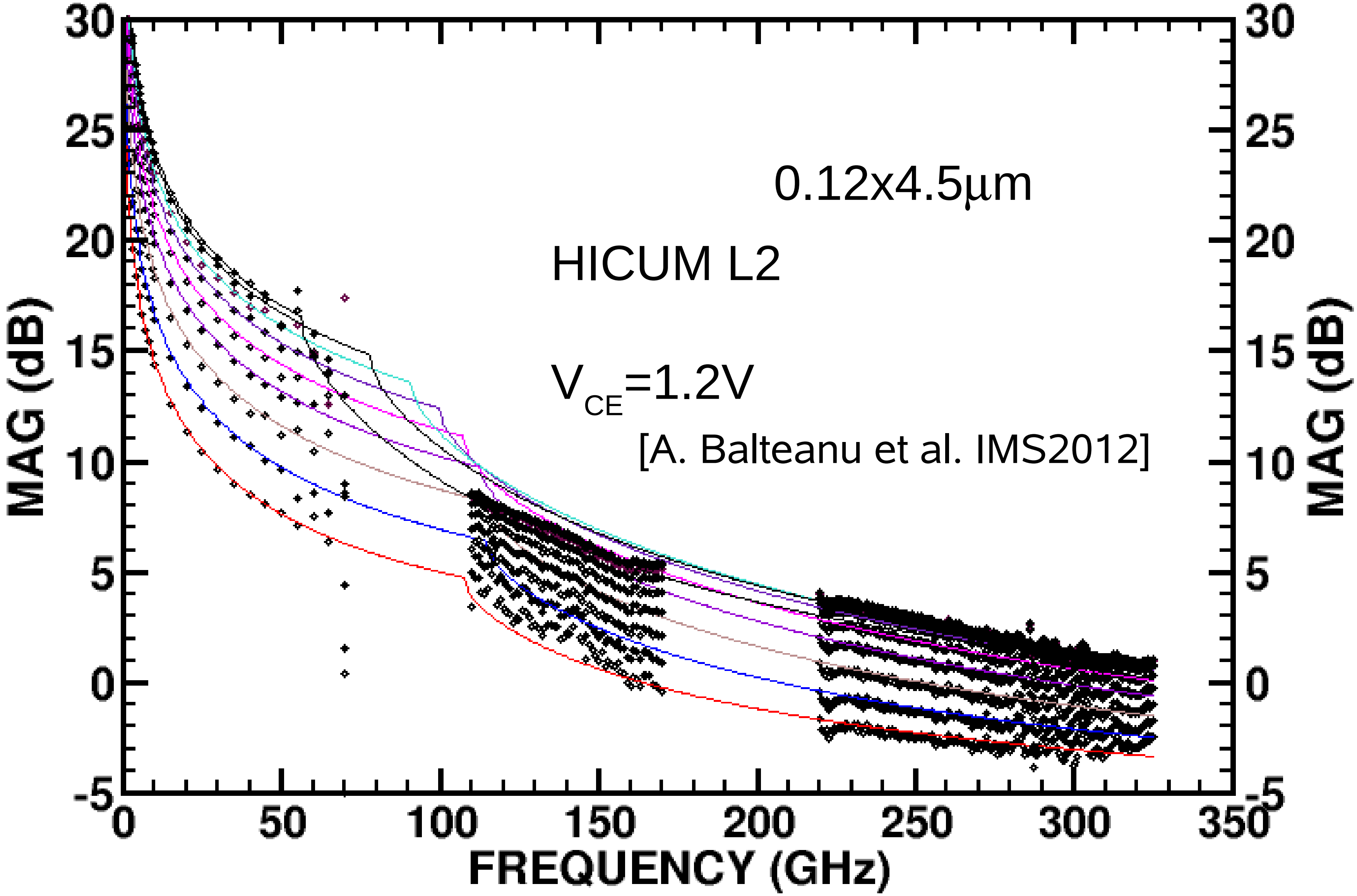
Source: G. Rebeiz UCSD

Technology: 280/400 GHz SiGe HBT

Mm-wave 6-metal Cu BEOL + Alucap



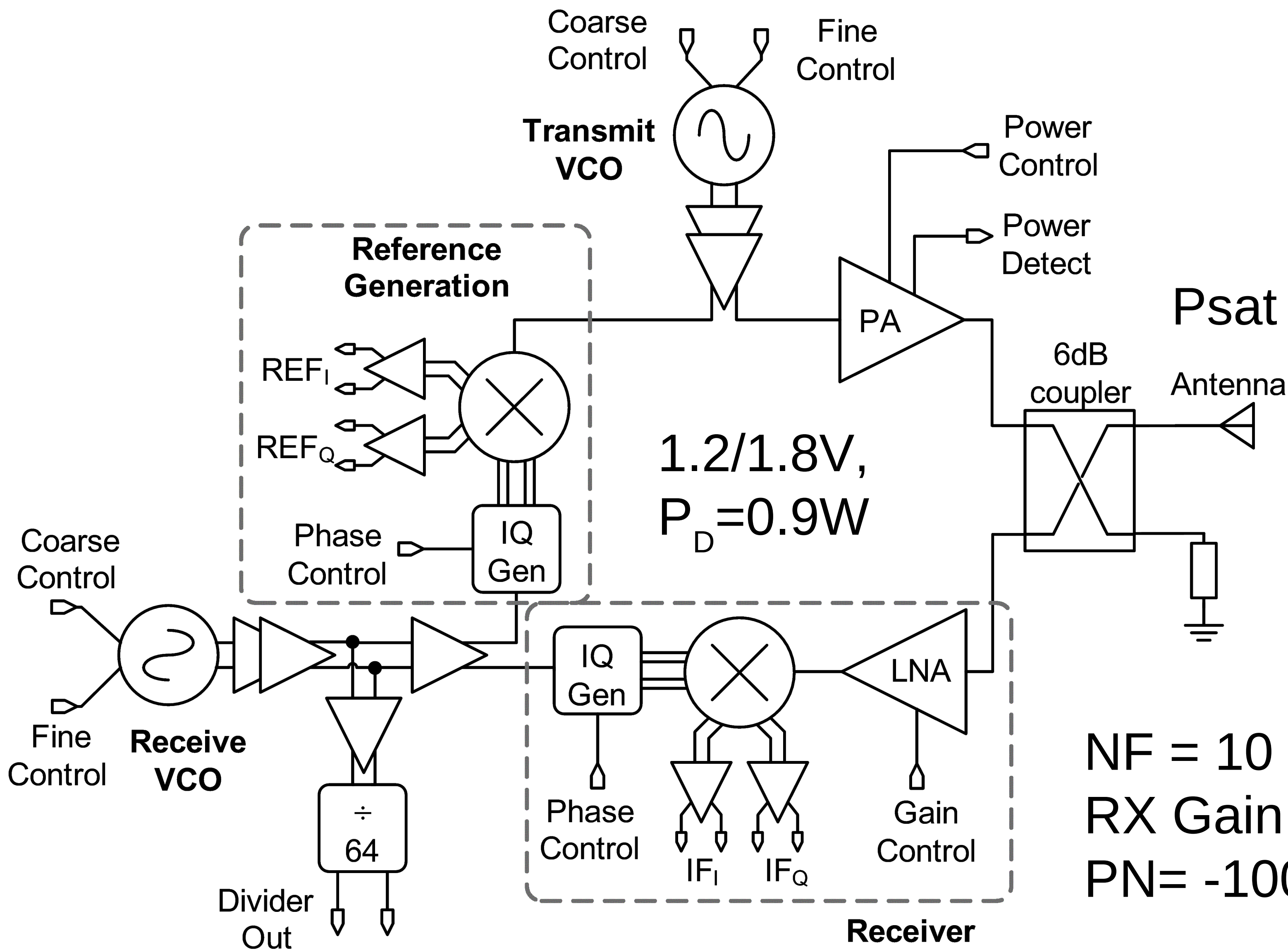
SiGe HBT Model Verification to 325 GHz



Outline

- Motivation
- Technologies
- 120-123 GHz Distance Sensor with above IC Antenna
- 150-170 GHz Transceiver with 3 on Die Antennas
- 143-150 GHz SUCCESS Sensor with BIST
- Potential Solutions for G-Band Sensors

120-GHz Distance Sensor



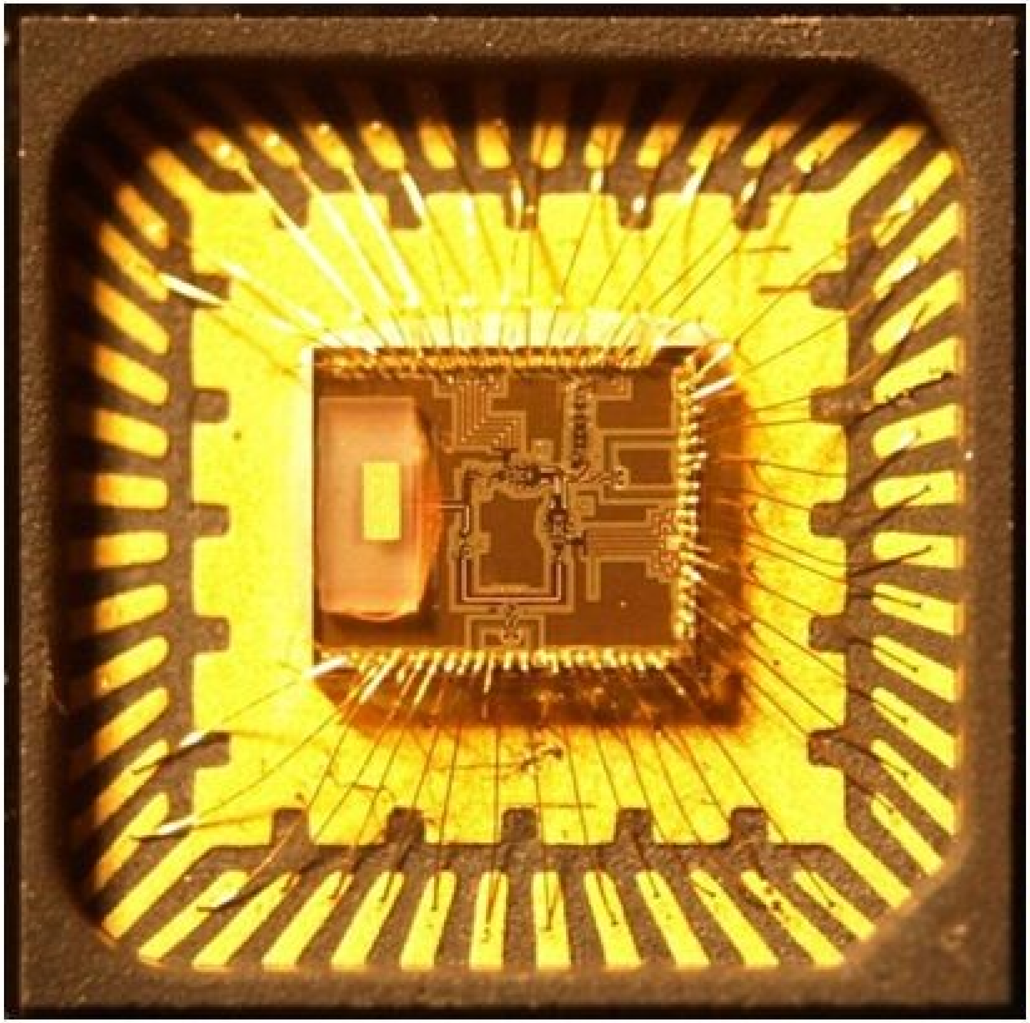
Psat > 3 dBm

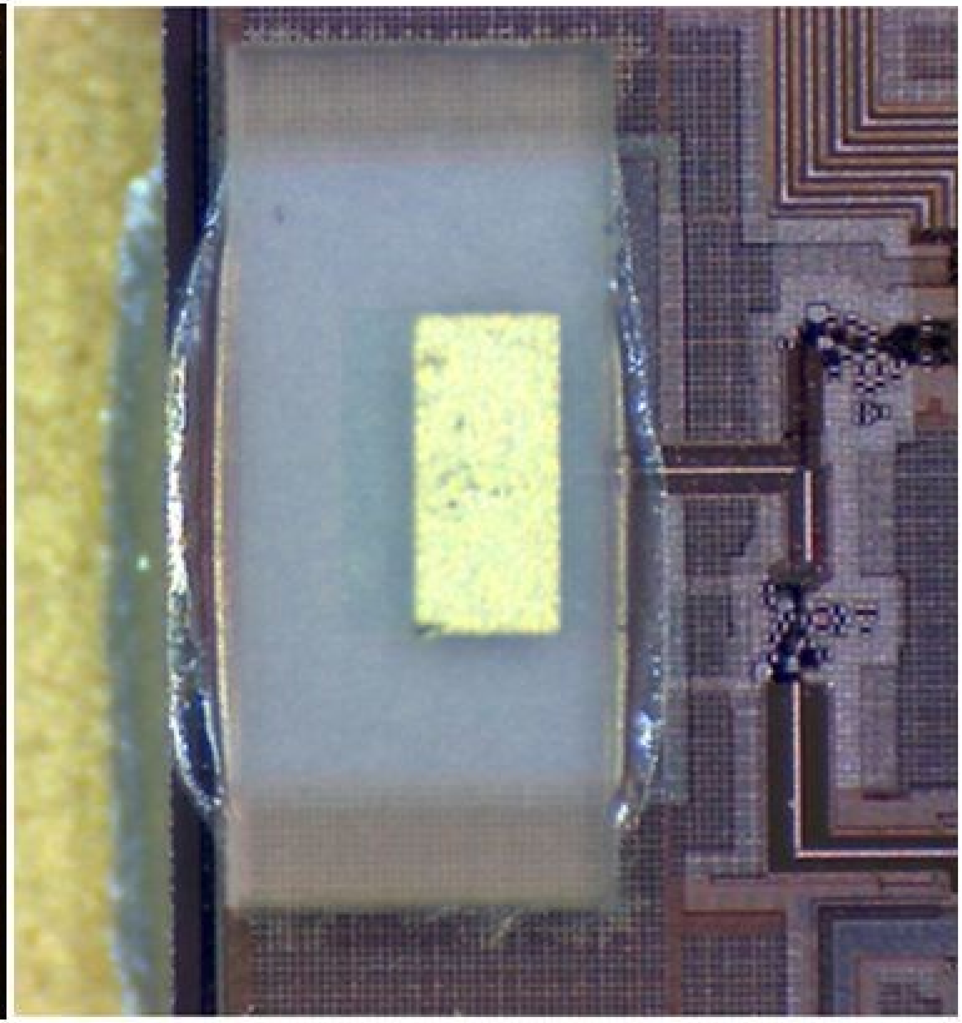
1.2/1.8V,
P_D=0.9W

NF = 10 dB
RX Gain = 12 dB
PN= -100 dBc/Hz

[I. Sarkas et al. Trans. MTT, March 2012]

Layout and Packaging





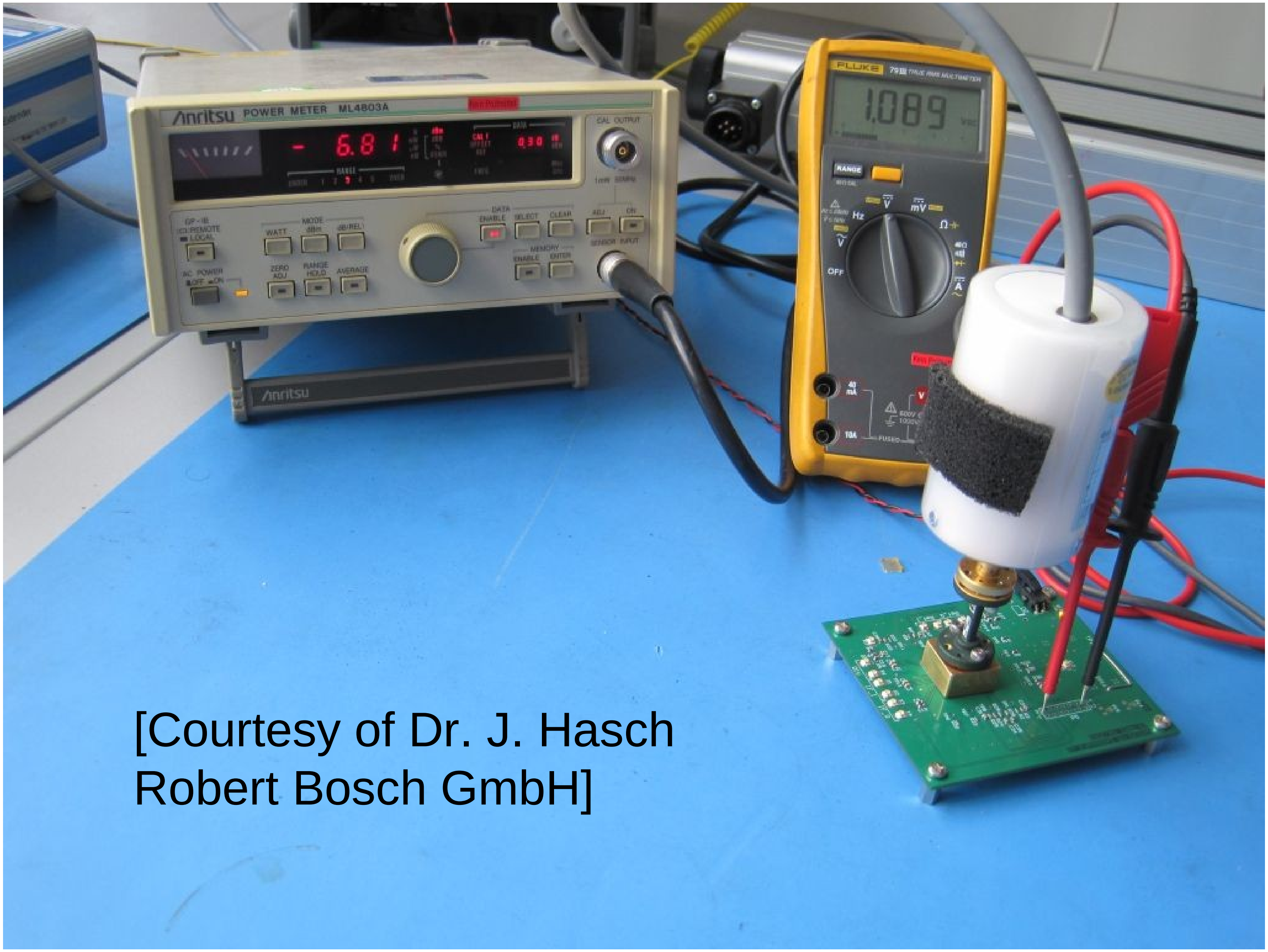
Chip: 2.2mm×2.6mm

Package: 7mm×7mm

Dr. J. Hasch

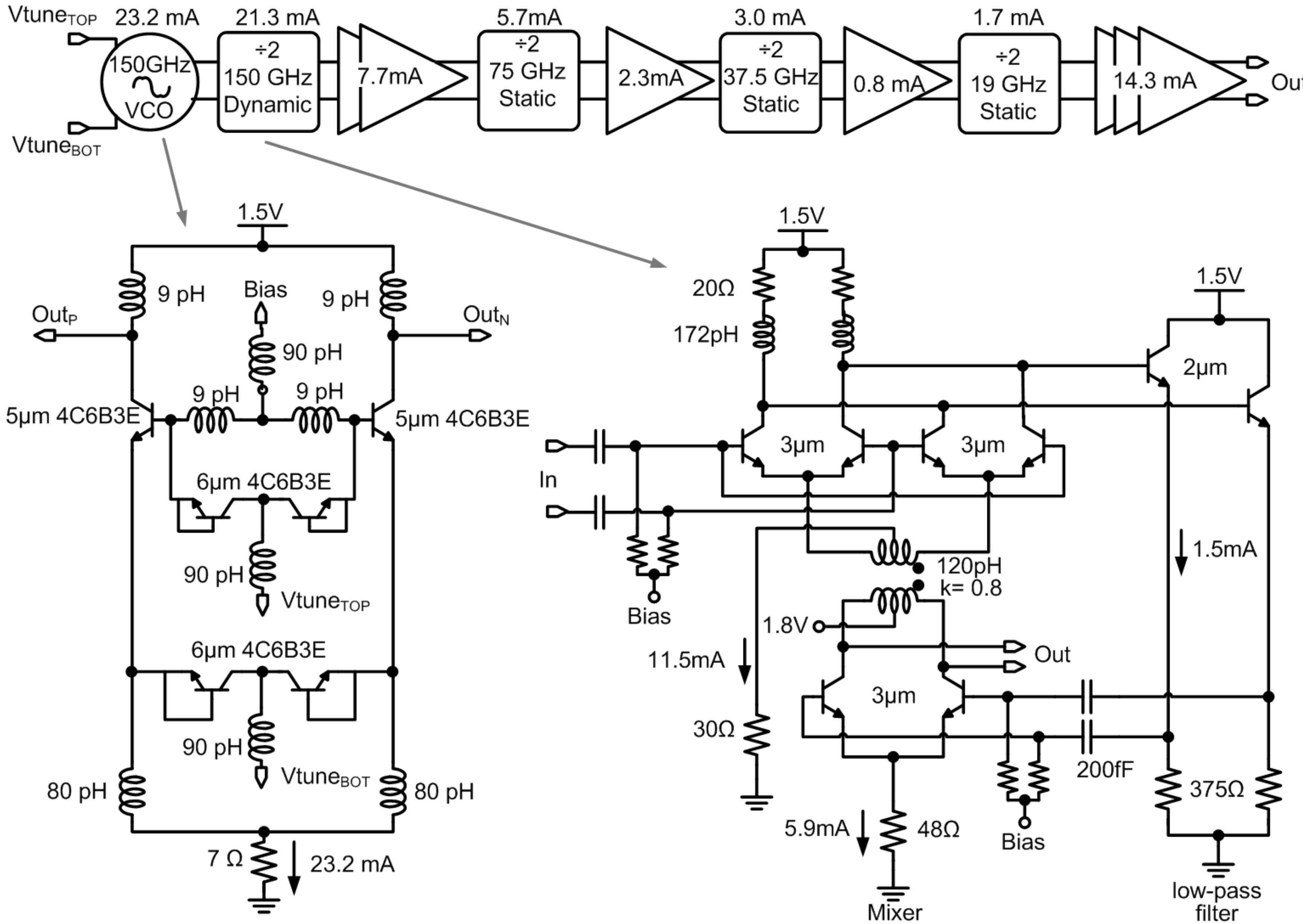
130-nm BiCMOS9MW: SiGe HBT f_T= 230 GHz, f_{MAX} = 280 GHz

Measured Output Power above Antenna



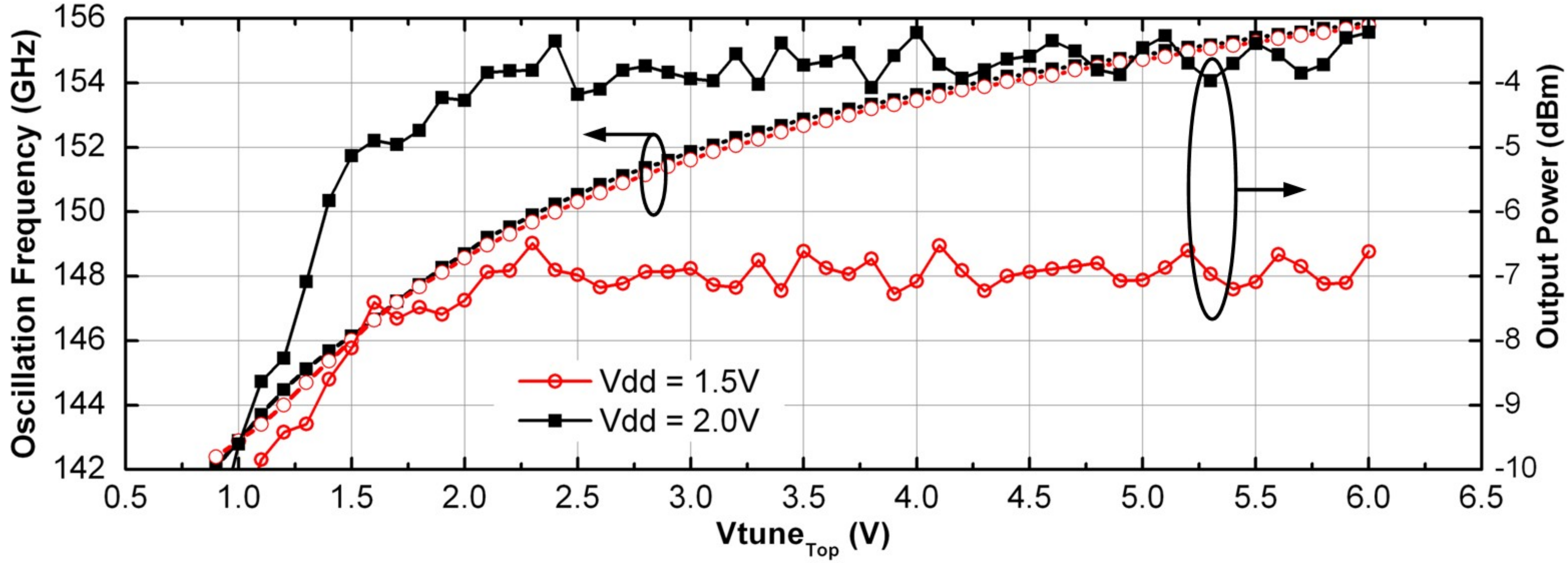
[Courtesy of Dr. J. Hasch
Robert Bosch GmbH]

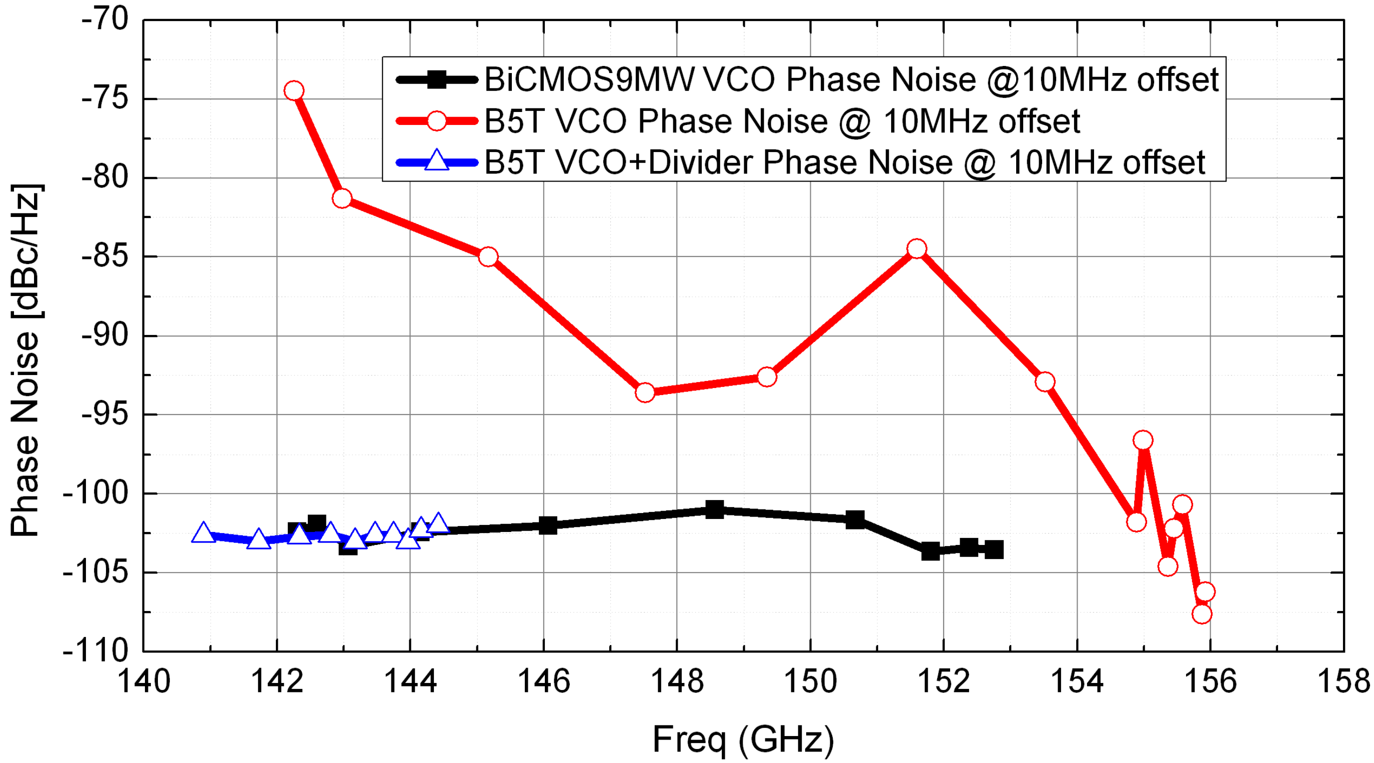
150-GHz VCO-prescaler



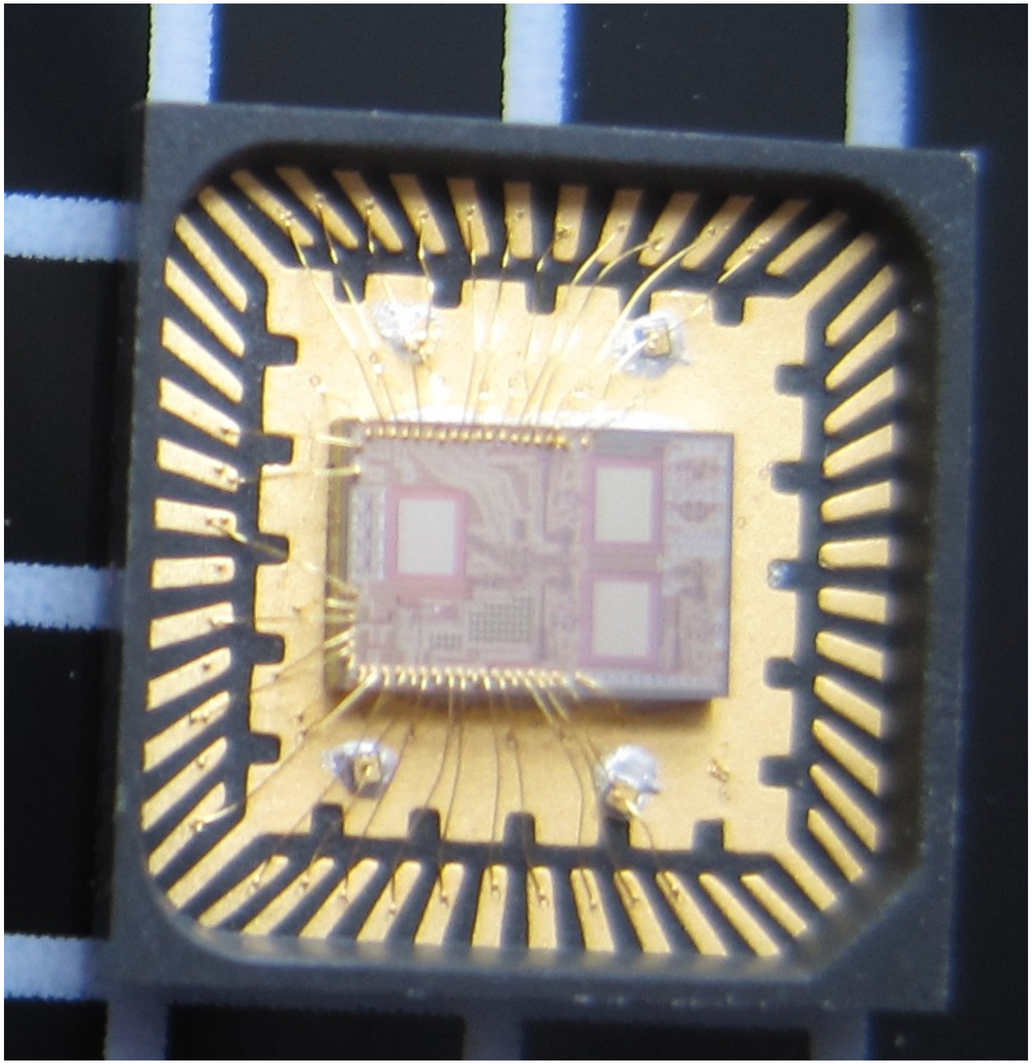
[A. Balteanu et al IMS 2012]

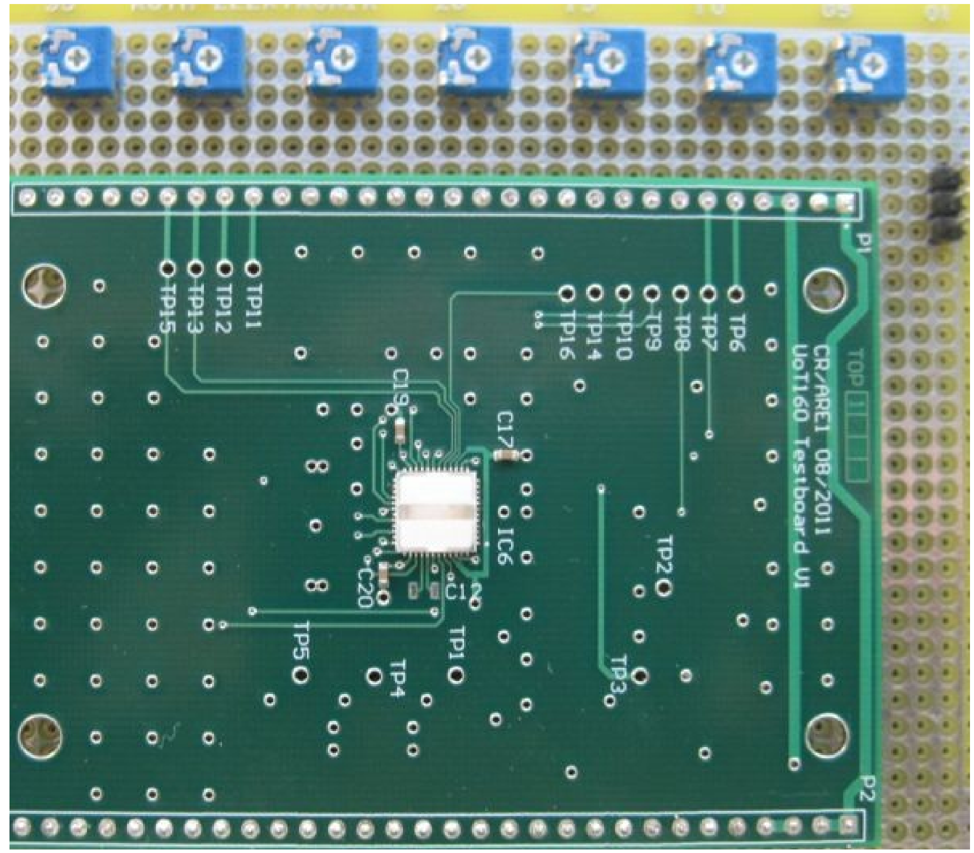
150-GHz VCO Synthesizer Measurements





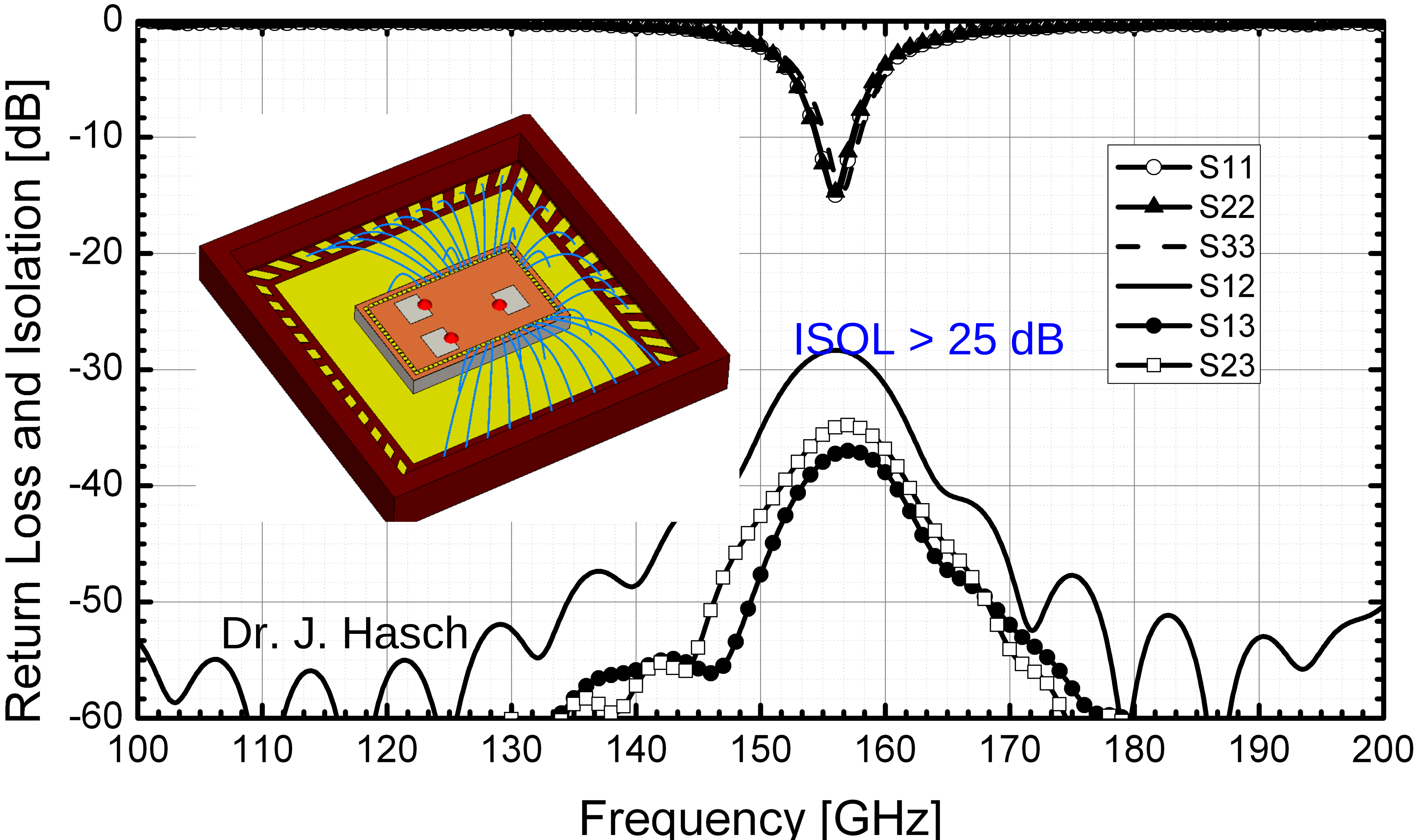
Packaging: QFN & wirebonding





[Courtesy of Dr. J. Hasch
Robert Bosch GmbH]

In-package antennas simulation



[Courtesy of Dr. J. Hasch
Robert Bosch GmbH]

Measured Pout and Phase Noise
300-GHz source: VCO+buffer+doubler